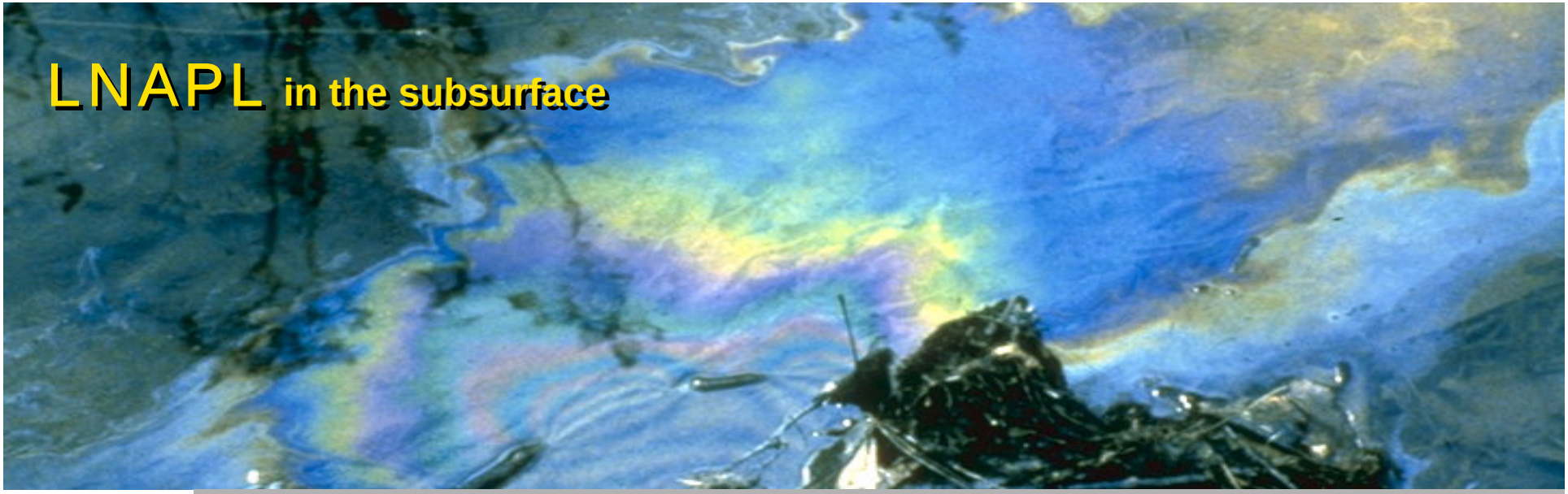

LNAPL Modeling
recovery and endpoint example

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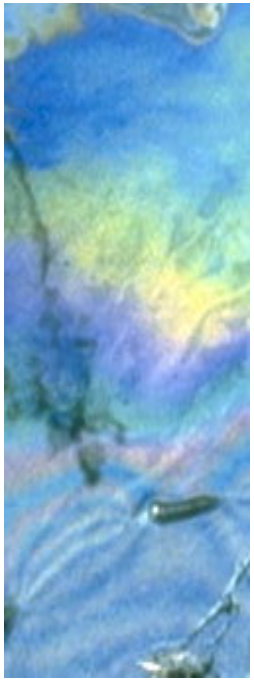
&

Mark Adamski, P.G.
Technical Specialist and Environmental Business Manager, BP America

Objective

1. Describe the API LNAPL Liquid Distribution and Recovery Modeling Tool (LDRM).
2. Demonstrate application of the modeling tool for a petroleum refinery.

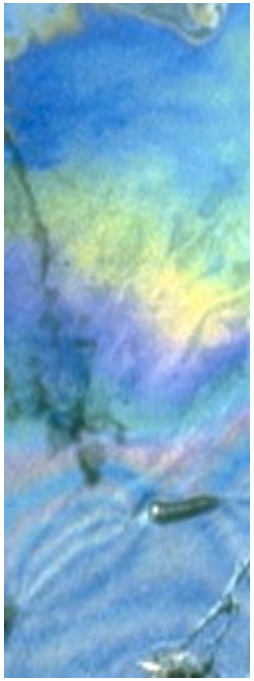


LNAPL Liquid Distribution and Recovery Modeling (LDRM) Tool

Purpose: provide a simple, physically based model to assess LNAPL distribution and recovery using conventional LNAPL liquid recovery technologies (single and dual-pump wells, vacuum-enhanced wells, skimmer wells, and trenches) based on LNAPL thickness in a monitoring well

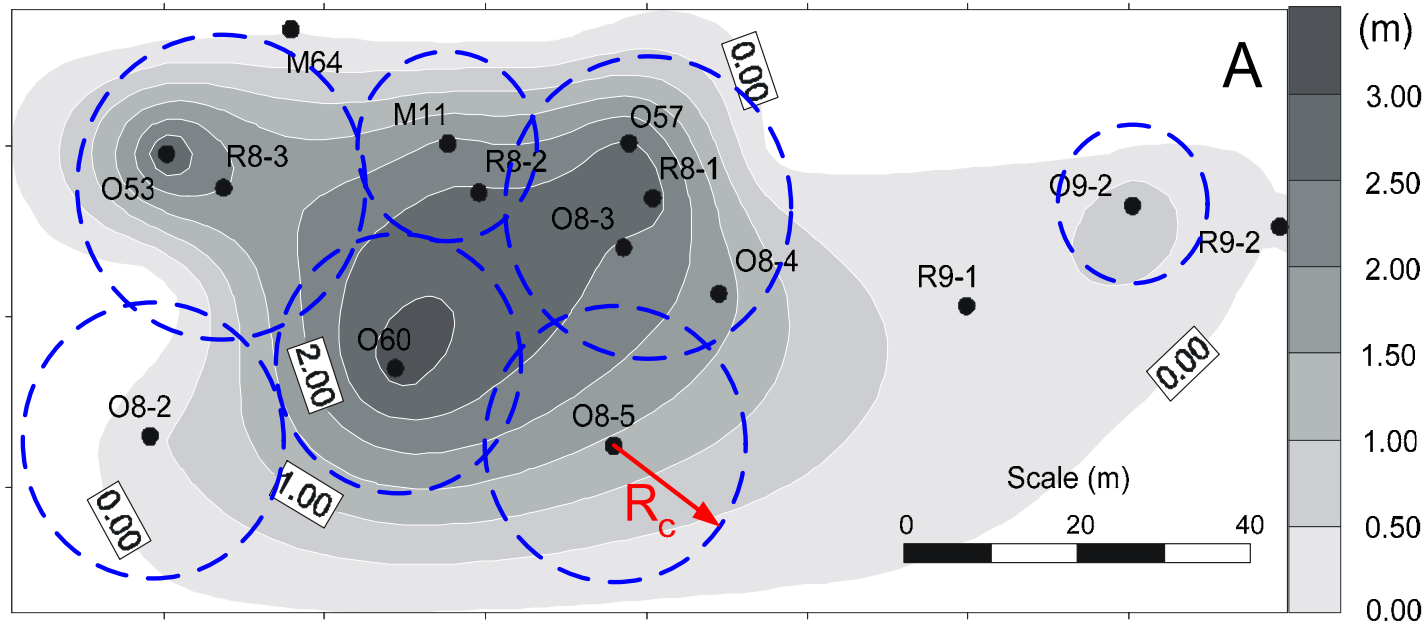
Chronology:

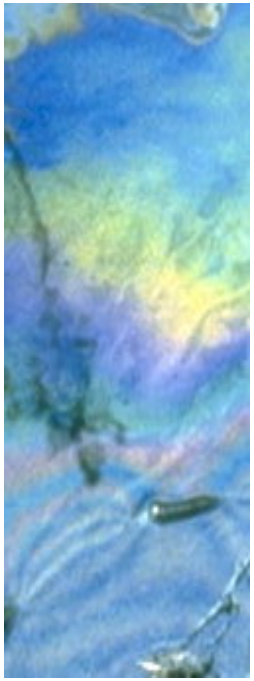
- 1999 Release (API #4682) – dual spreadsheet model using Brooks and Corey parameters and a simplified relative permeability function (based on the Burdine equations)
- 2003 Release (API #4729) – multiple spreadsheets (stand alone) using van Genuchten parameters with different spreadsheets for Burdine and Mualem relative permeability models, and for single and two-layer representations
- 2007 Release (API 4760) – single “Windows” application using van Genuchten parameters with option of 1-, 2- or 3-layers, relative permeability models, units, data representation, and vertical gradient through FGS



Recovery Well Application

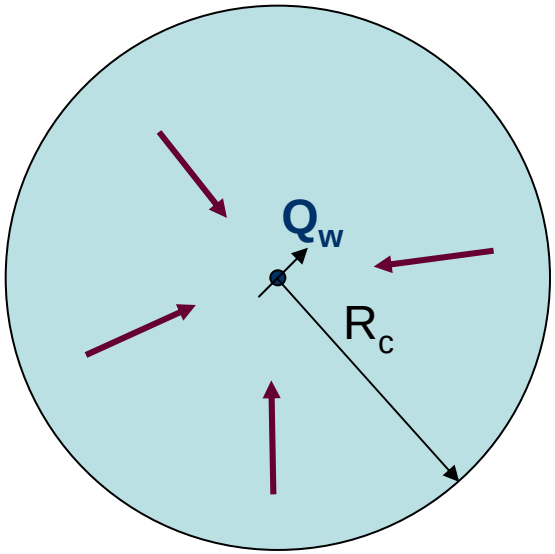
LNAPL Plume may be covered by multiple capture regions, each considered separately





Scenario-Based Model

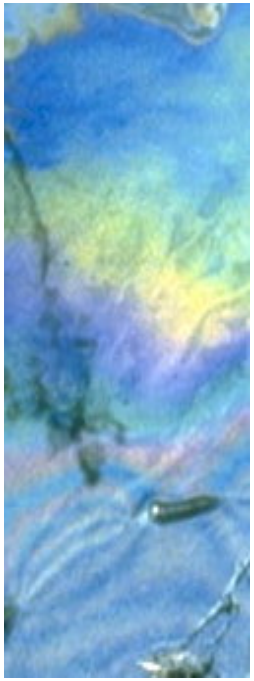
Model Domain Consists Only of a "Capture Region"



Radial Flow to a Recovery Well

Required Site Parameters

- LNAPL thickness, b_n
- Ground surface elevation, z_{gs}
- Water table elevation, z_{wt}
- Elevation of soil facies interface, z_{12}, z_{23}



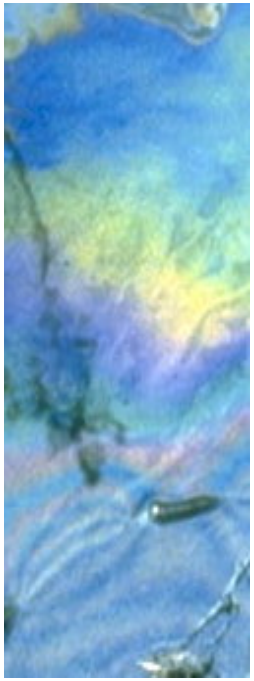
Required Soil and Fluid Parameters

Soil Parameters

- Porosity, n
- Hydraulic conductivity, K_{ws}
- Van Genuchten, α
- Van Genuchten, N
- Irreducible Water Saturation, S_{wr}

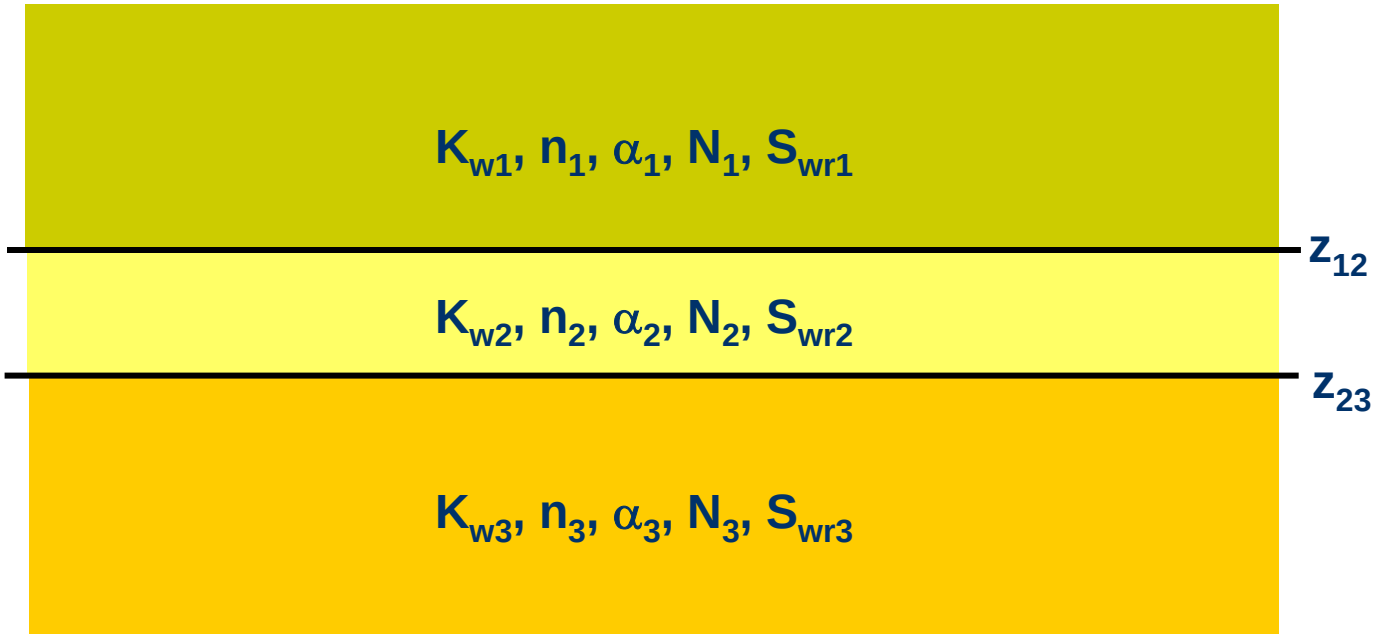
Fluid Parameters

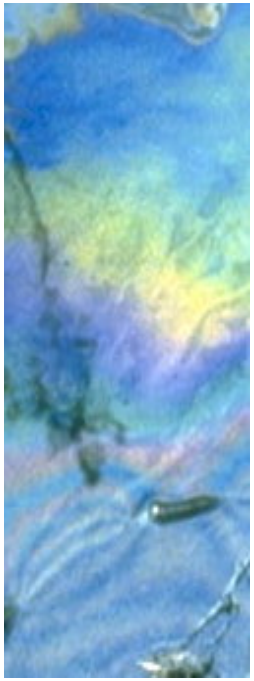
- LNAPL density (ratio), ρ_r
- LNAPL viscosity (ratio), μ_r
- Air/water surface tension, σ_{aw}
- Air/LNAPL surface tension, σ_{an}
- LNAPL/water interfacial tension, σ_{nw}



Soil Heterogeneity

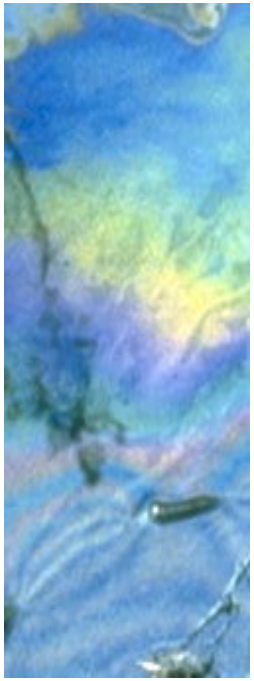
Up to three soil layers with abrupt vertical facies transition



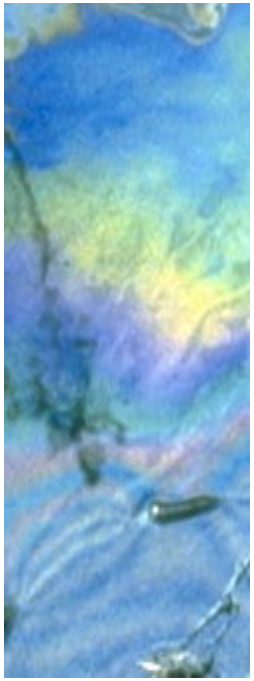


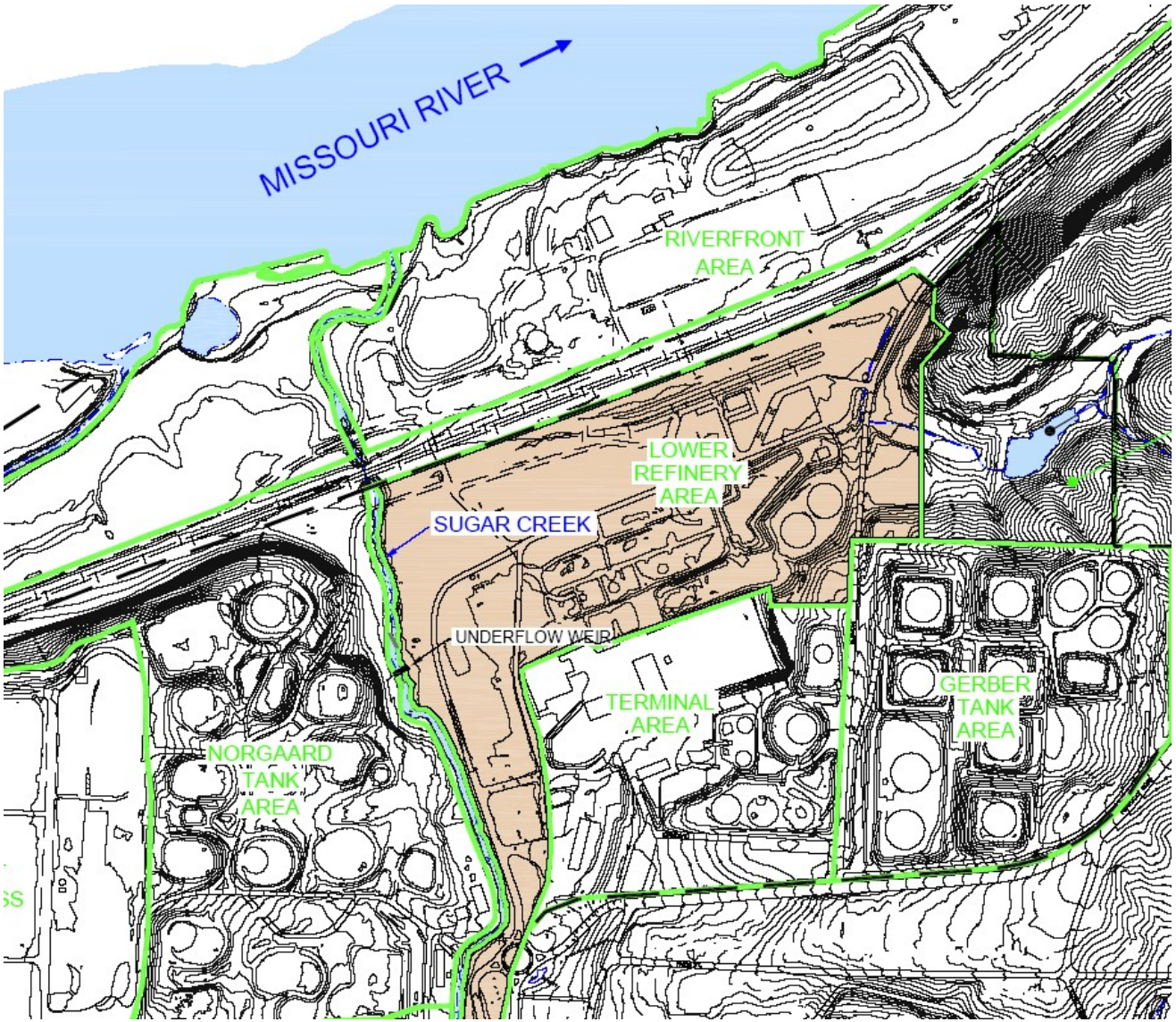
Well Parameters

- **Recovery time, T_R**
- **Radius of pumping well, R_W**
- **Radius of capture, R_C**
- **Radius of Influence, R_I**
- **Groundwater production rate, Q_w**
- **Water saturated thickness at well, b_w**
- **Suction pressure (vacuum-enhanced system), P_v**
- **Screen length (vadose zone), b_a**
- **Air radius of capture, R_A**
- **→ If $Q_w = 0$ and $P_v = 0$ then Skimmer Well is assumed**



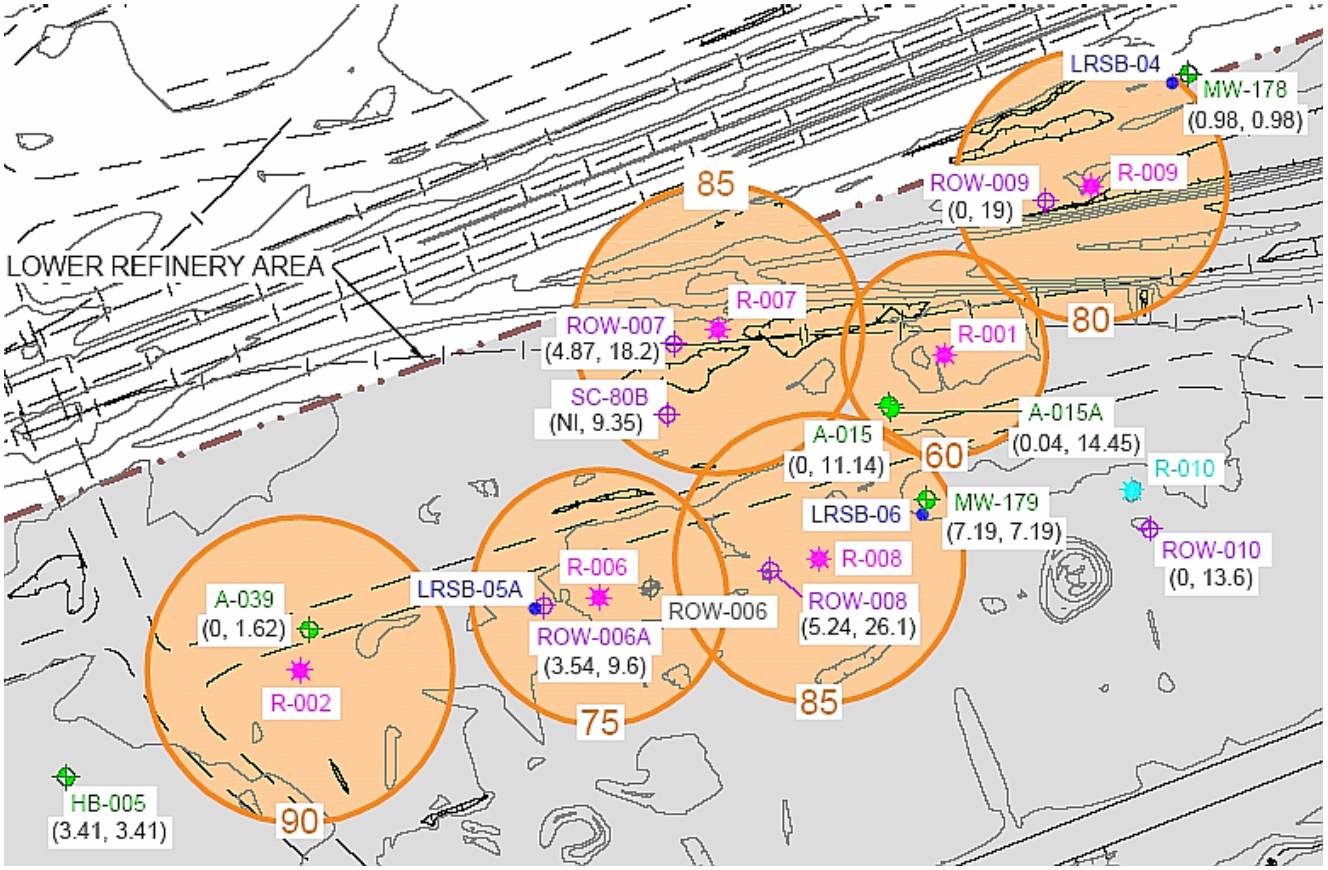
Application to a Closed Refinery Site Located Near the Missouri River

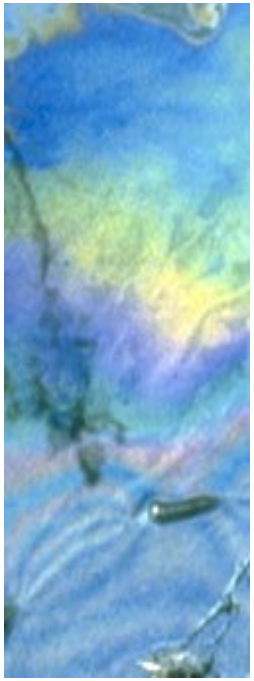




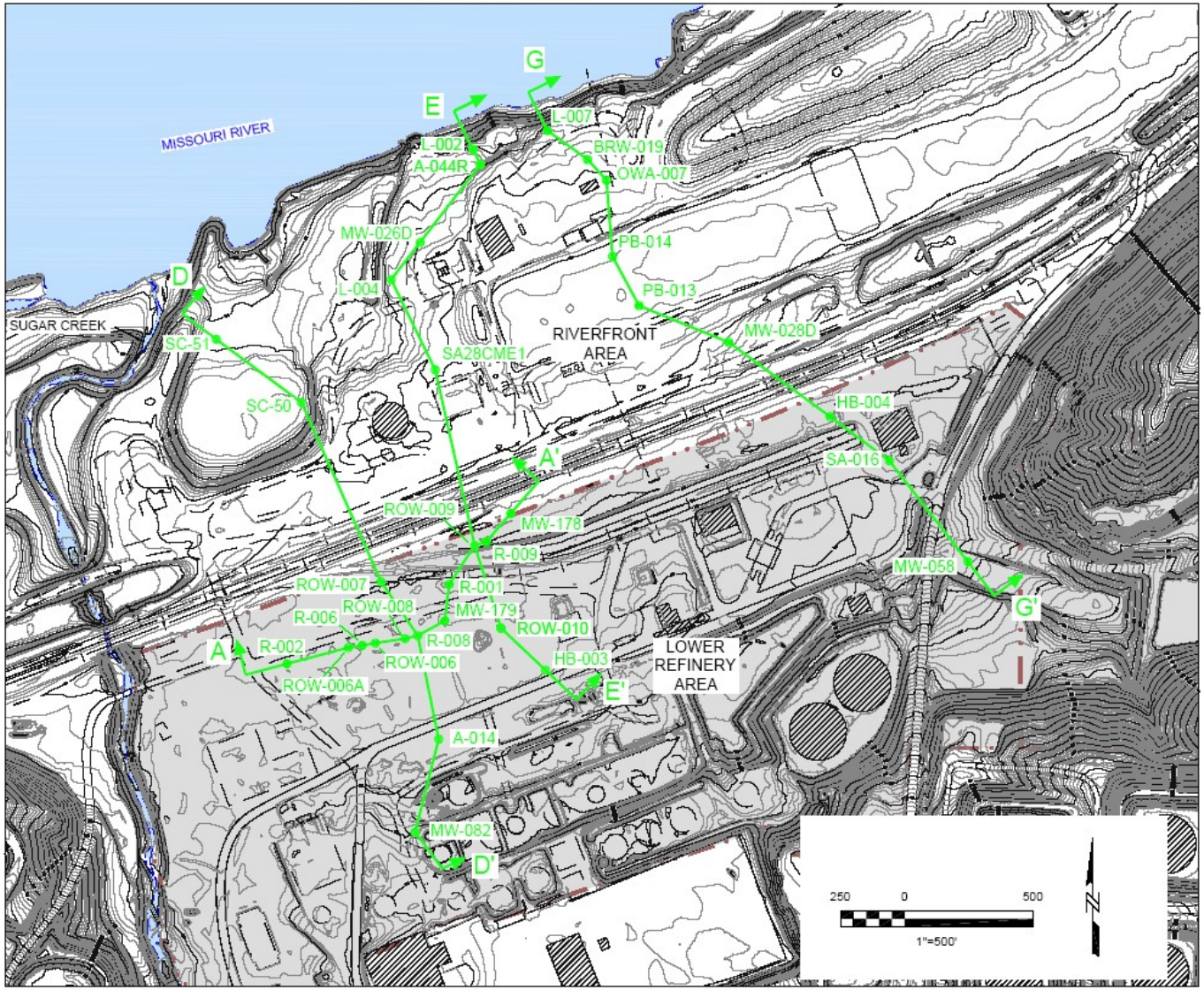
Application of LLRM

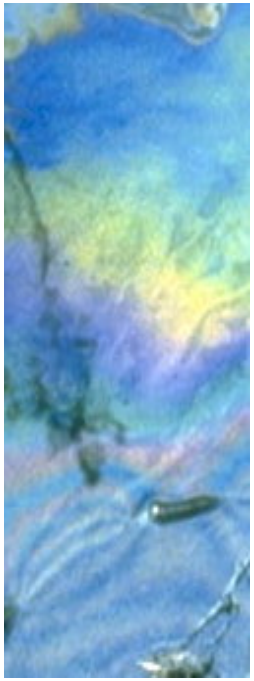
Recovery well at a industrial site in the Midwestern U.S.



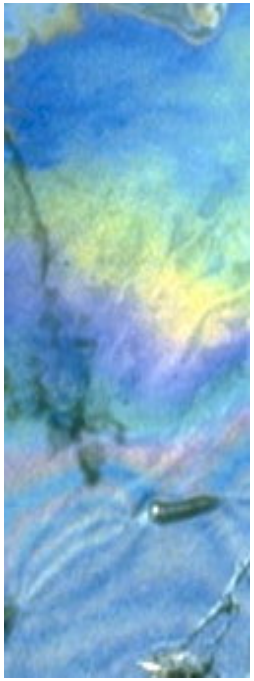


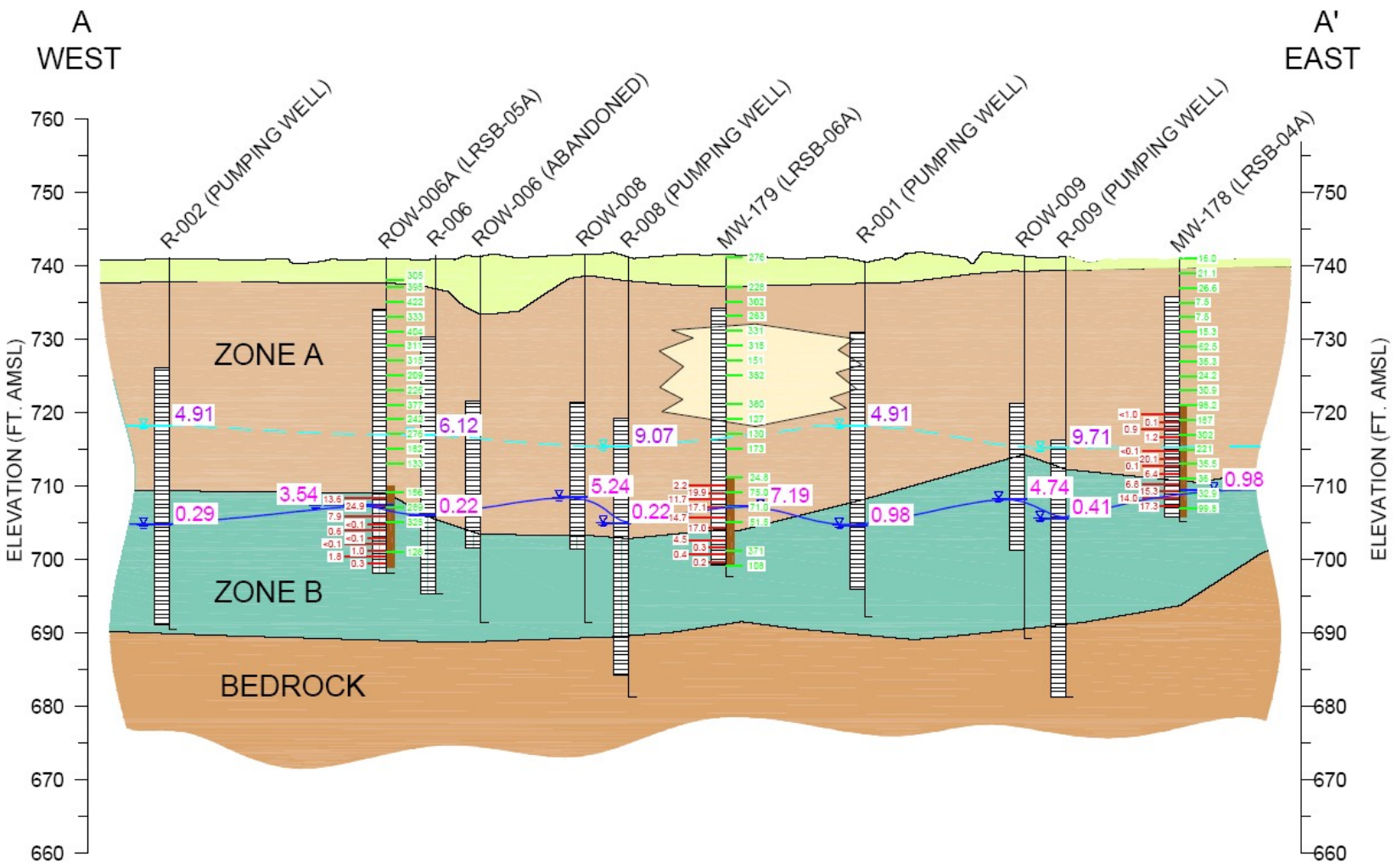
Cross-Section Layout





Cross-Section A-A’

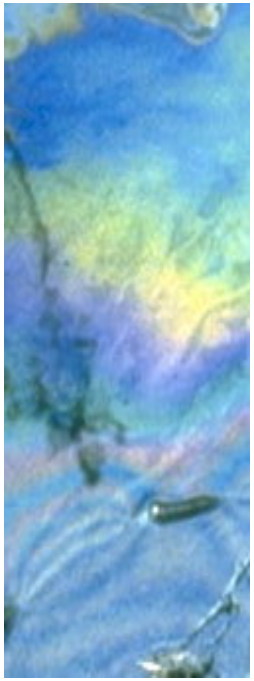




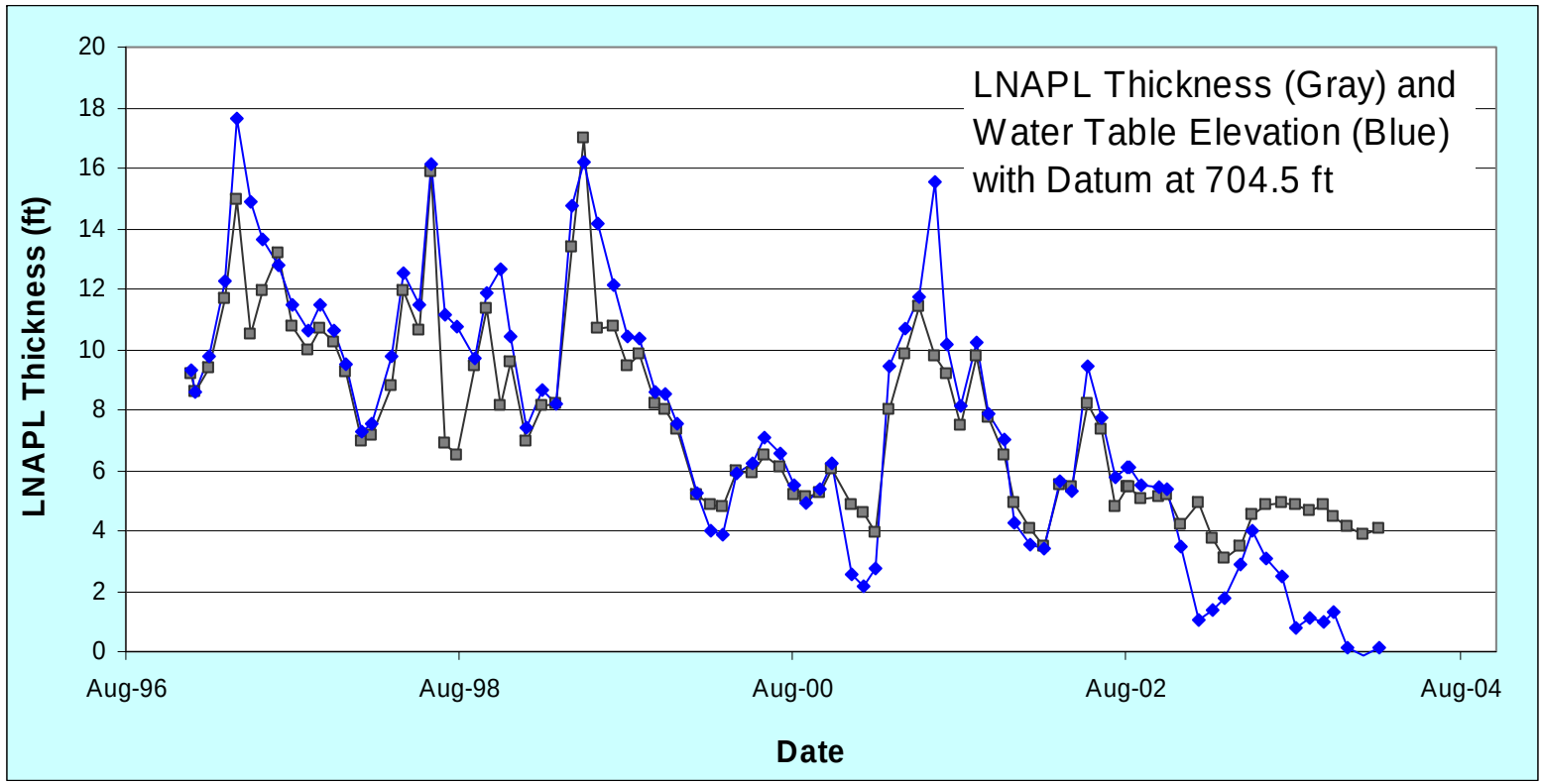
Site-Specific Data

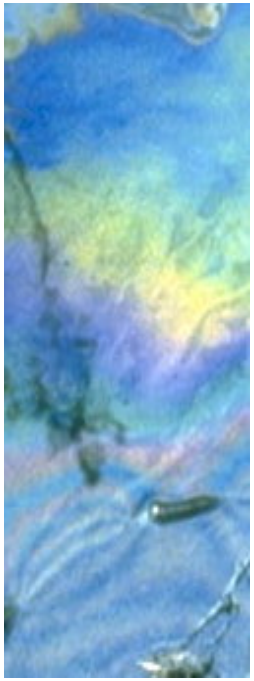
- **Recovered fluid measurements**
  - LNAPL density and viscosity
  - Surface and interfacial tension values
- **Soil core measurements**
  - Grain size distribution
  - Capillary pressure curves
  - Hydraulic conductivity
- **LNAPL saturation (Dean Stark method)**

- **Site-specific**
  - LNAPL recovery rates
  - Groundwater recovery rates



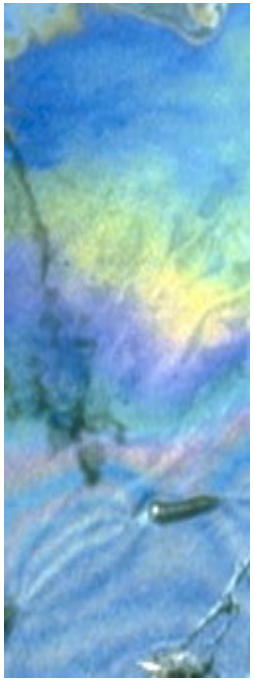
LNAPL Thickness and Water Table Elevation





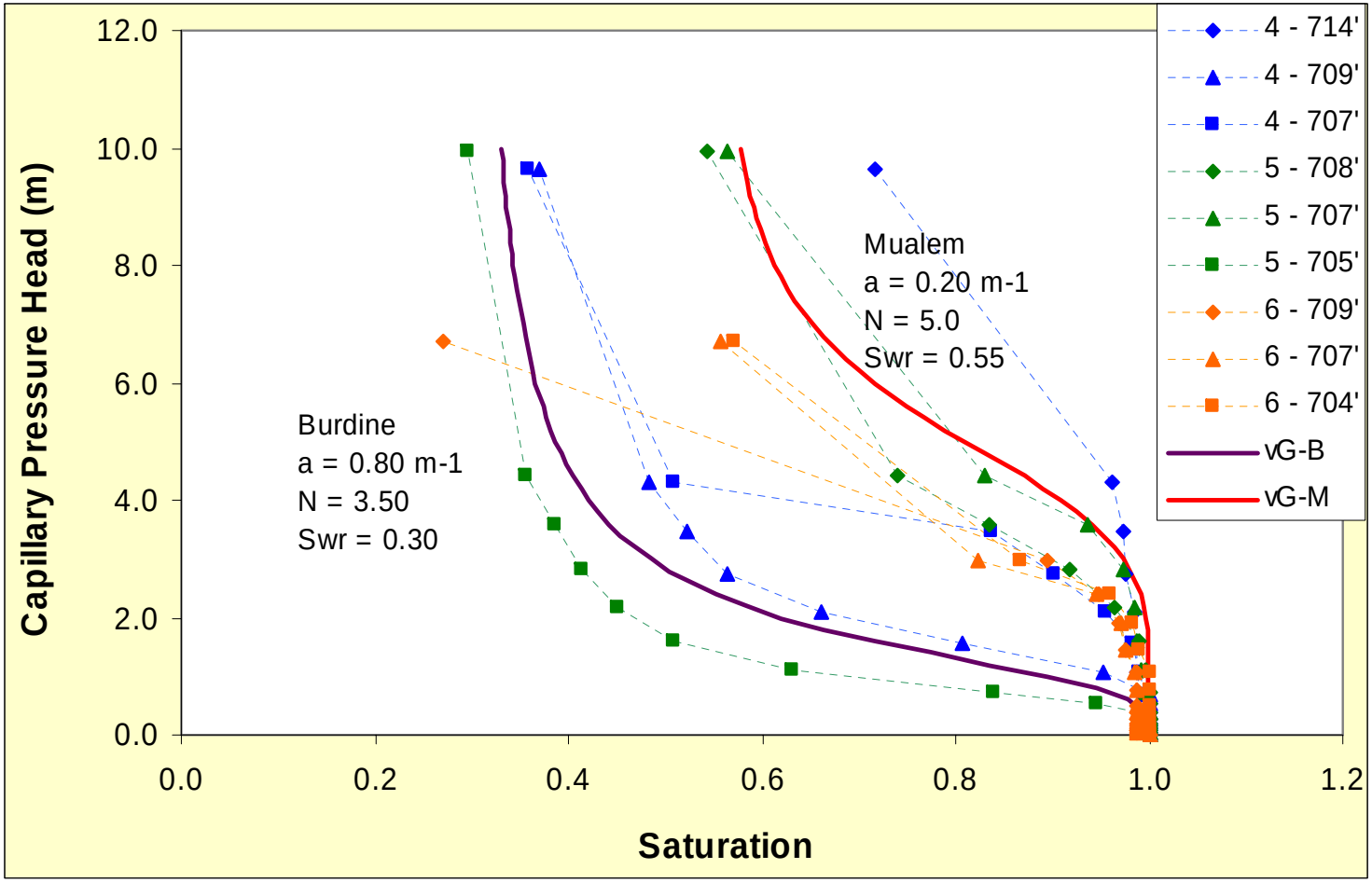
Monitoring Well Data

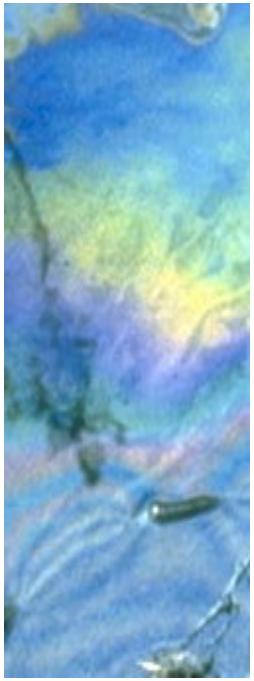
These data suggest that for this site with LNAPL trapped beneath FGZ, monitoring well LNAPL thickness will probably be a poor indicator of the amount of LNAPL present within the subsurface



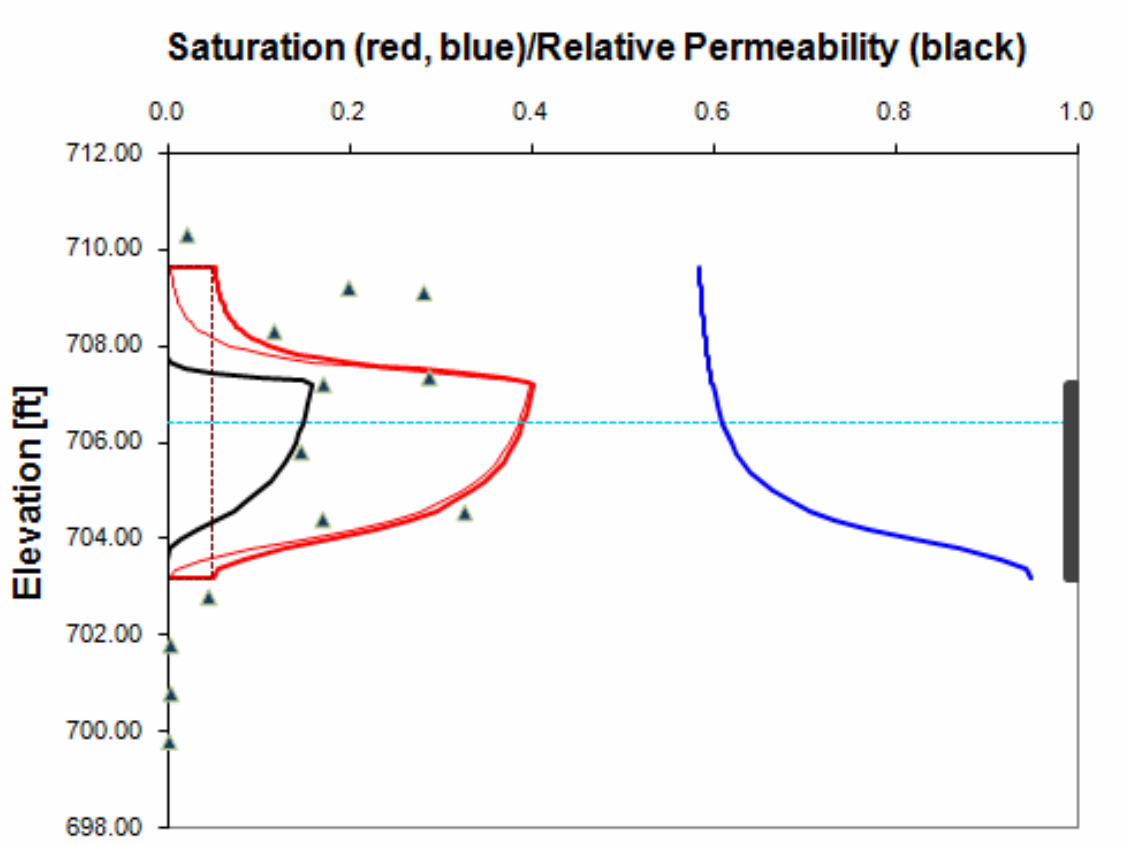
- **Application of LDRM with no model calibration**

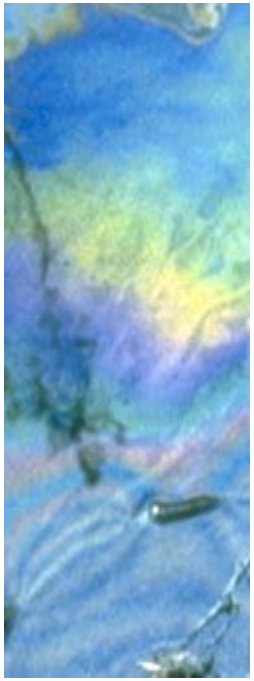
Fitting Capillary Pressure Curves – General Case



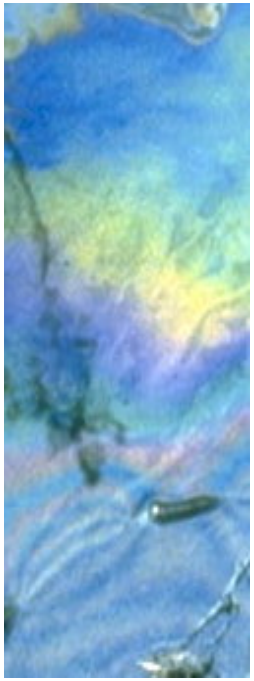


Early 1-Layer Model Representation





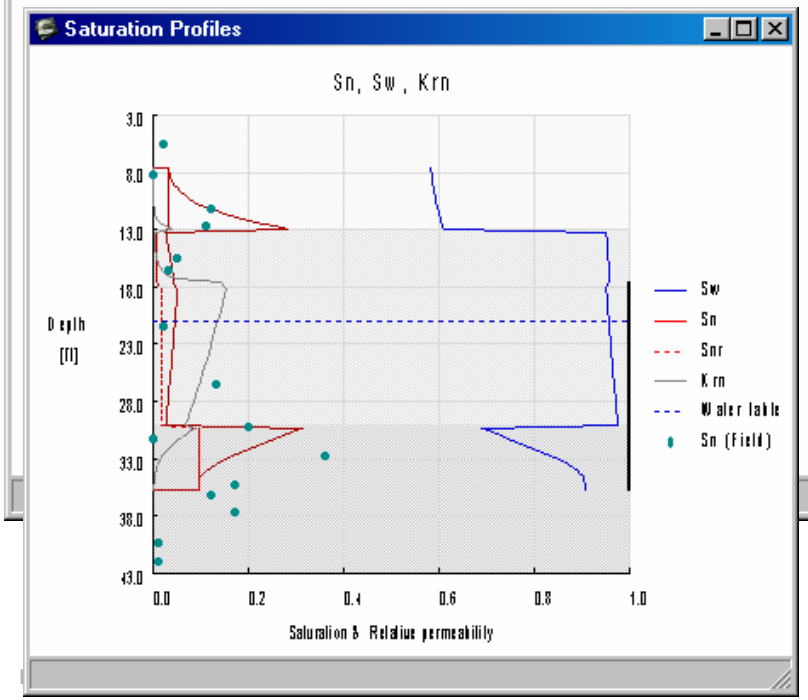
Groundwater Pumping and Lowered Water Table (Smearing)

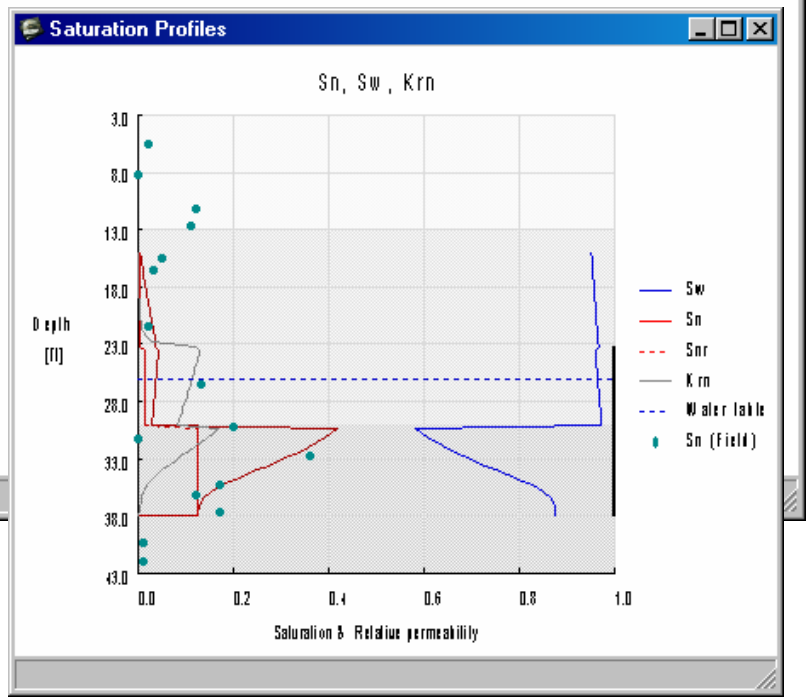


LNAPL Distribution and Recovery Model (LDRM)

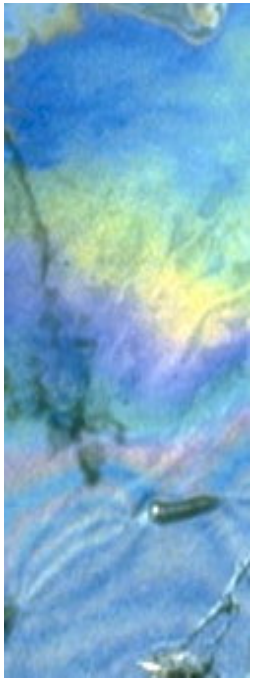
File Data Well Trench Graphs LNAPL Dist. Help Exit

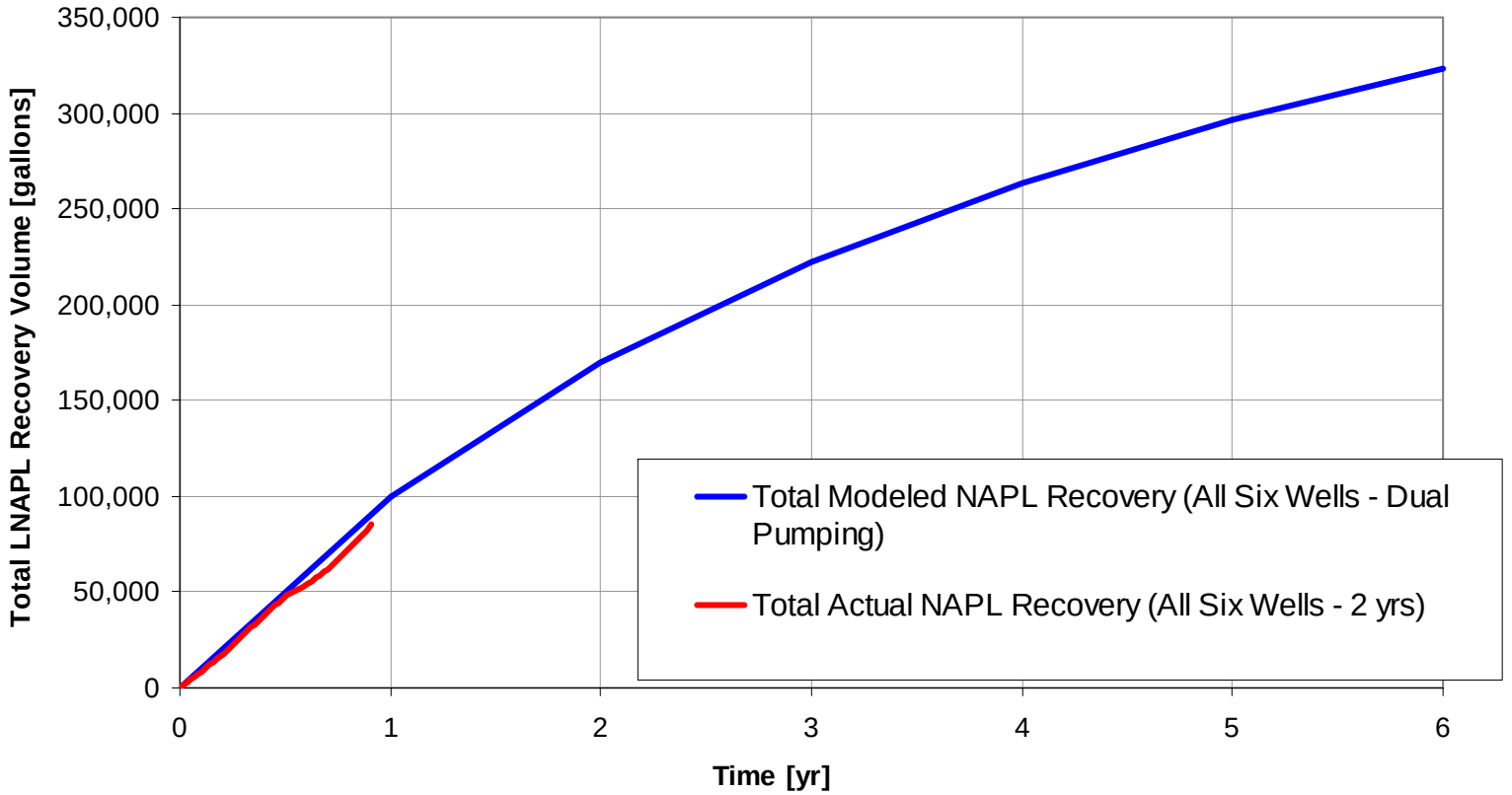
LNAPL Specific Volume, Dn (ft) =	0.908522
LNAPL Recoverable Volume, Rn (ft) =	0.551922
Drawdown (ft) =	4.989
New Water-table Elevation (ft) =	25.989
New LNAPL Thickness, bn (ft) =	14.788
New LNAPL Specific Volume, Dn (ft) =	0.845635
New LNAPL Recoverable Volume, Rn (ft) =	0.462857
Percent Recovery =	27.868



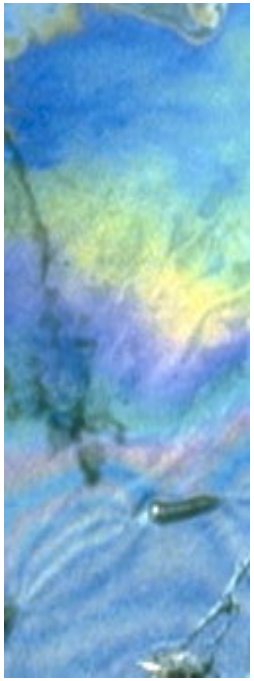


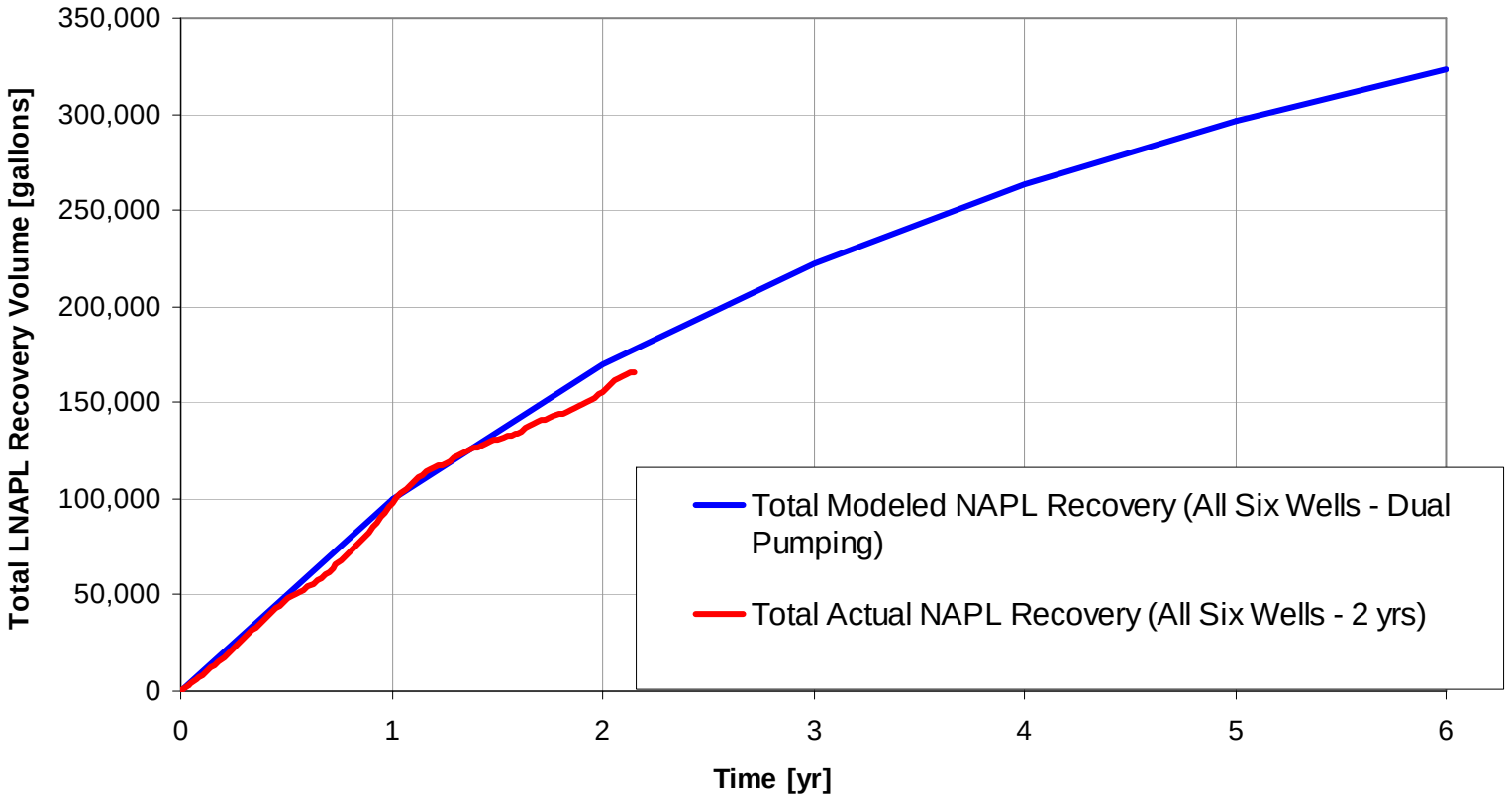
Initial Recovery Estimate for all Wells





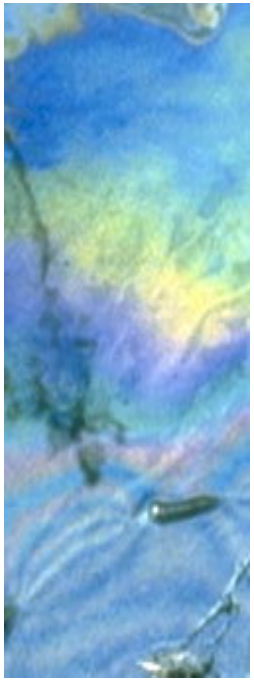
LNAPL recovery – model predicted and actual (2 years)



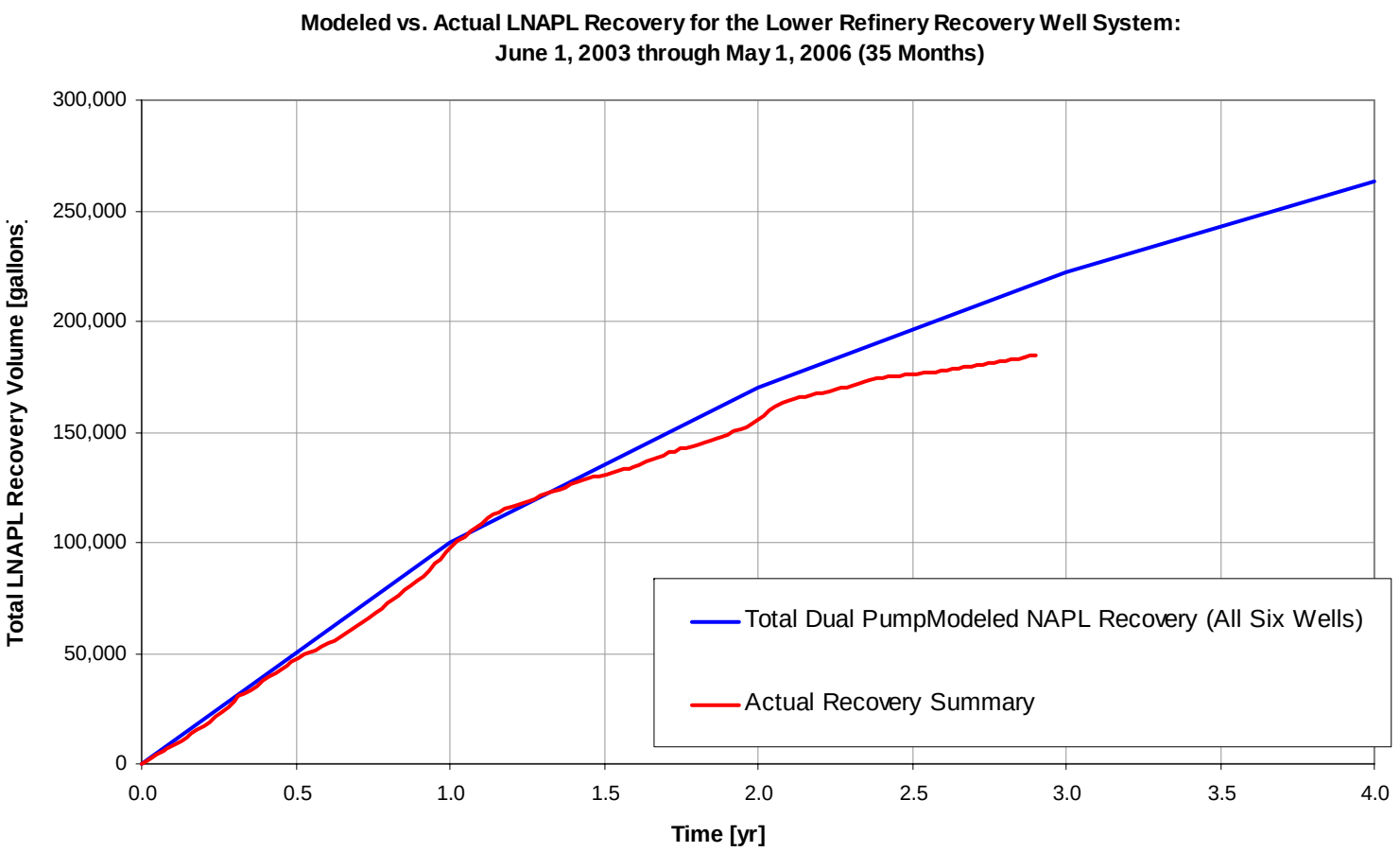


LNAPL in the subsurface

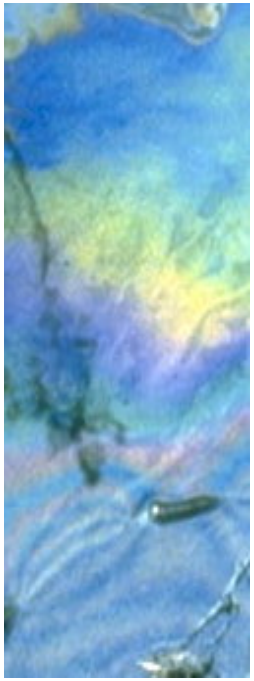
LNAPL recovery – model predicted and actual (2.75 years)



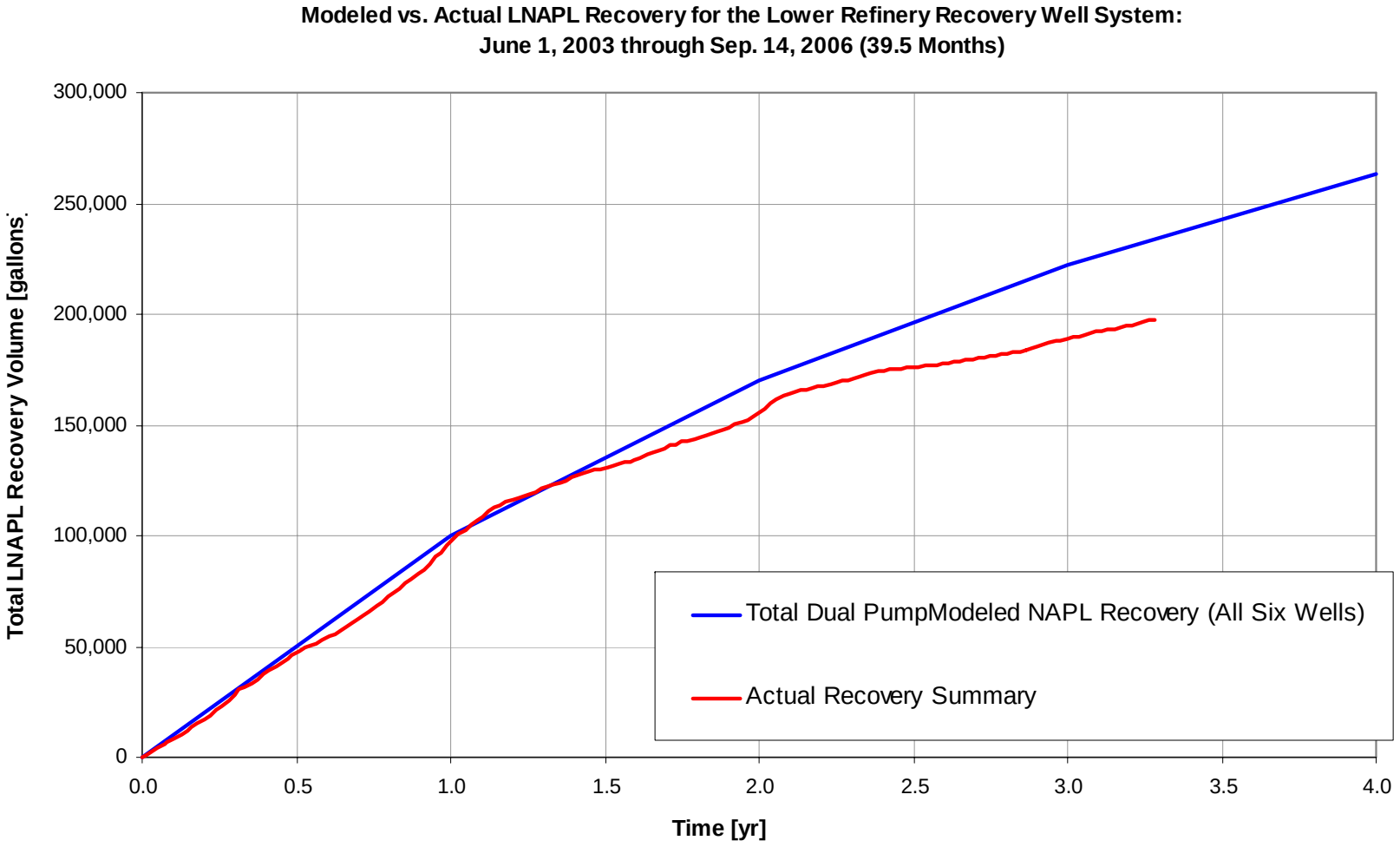
LNAPL in the subsurface



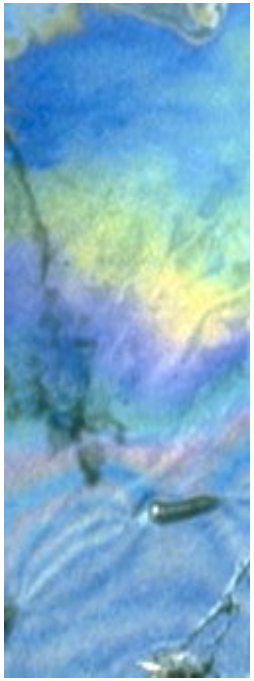
LNAPL recovery – model predicted and actual (3.25 years)

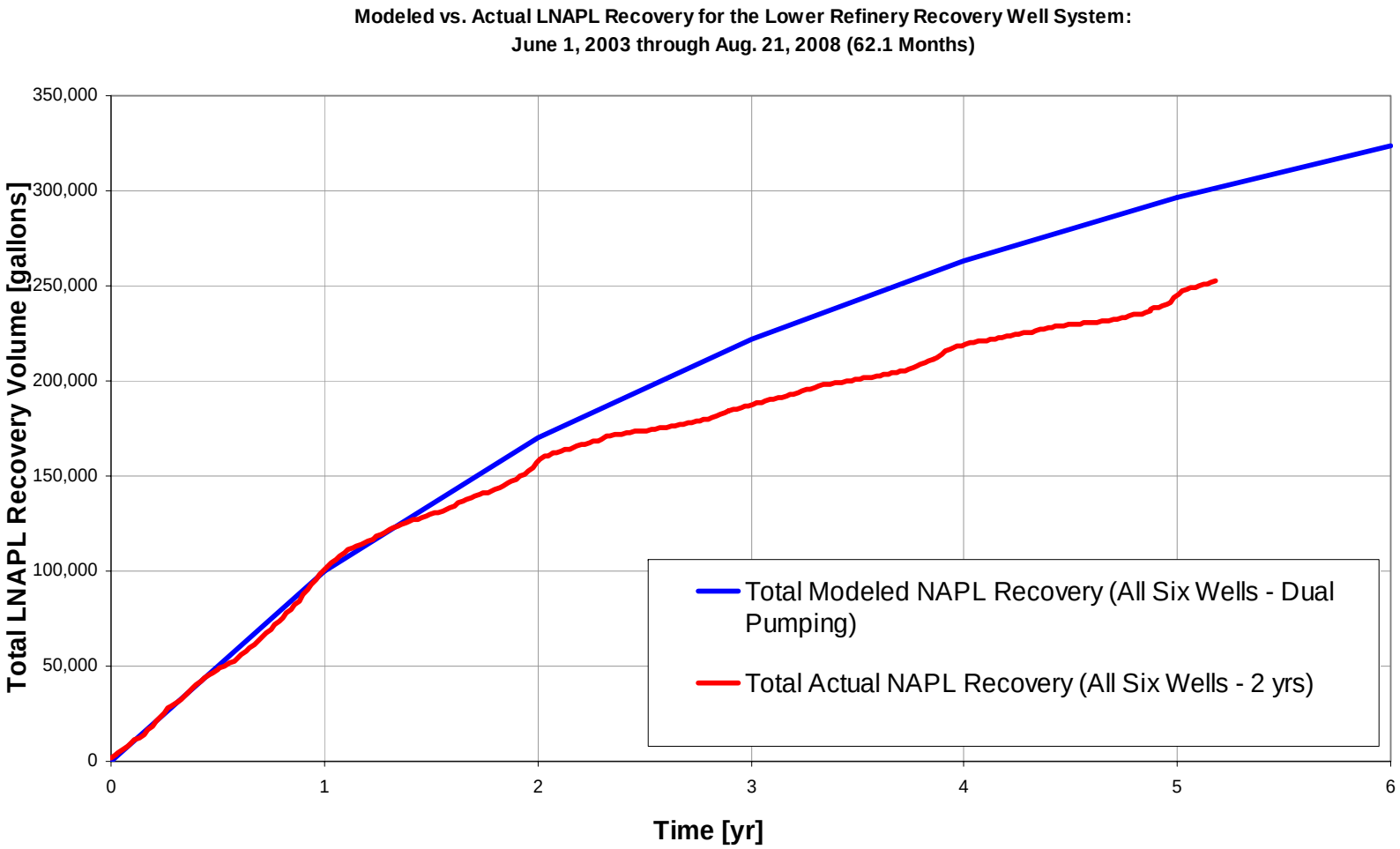


LNAPL in the subsurface



LNAPL recovery – model predicted and actual (5.25 years)

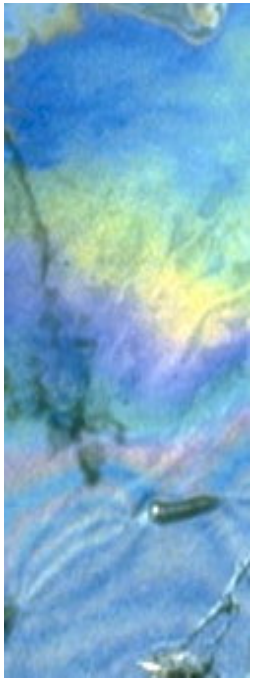




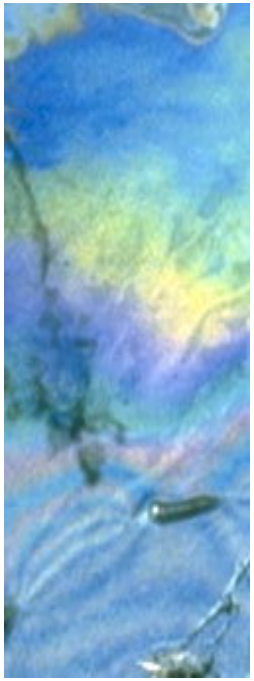
Why was the model off? (not that it was very far off)

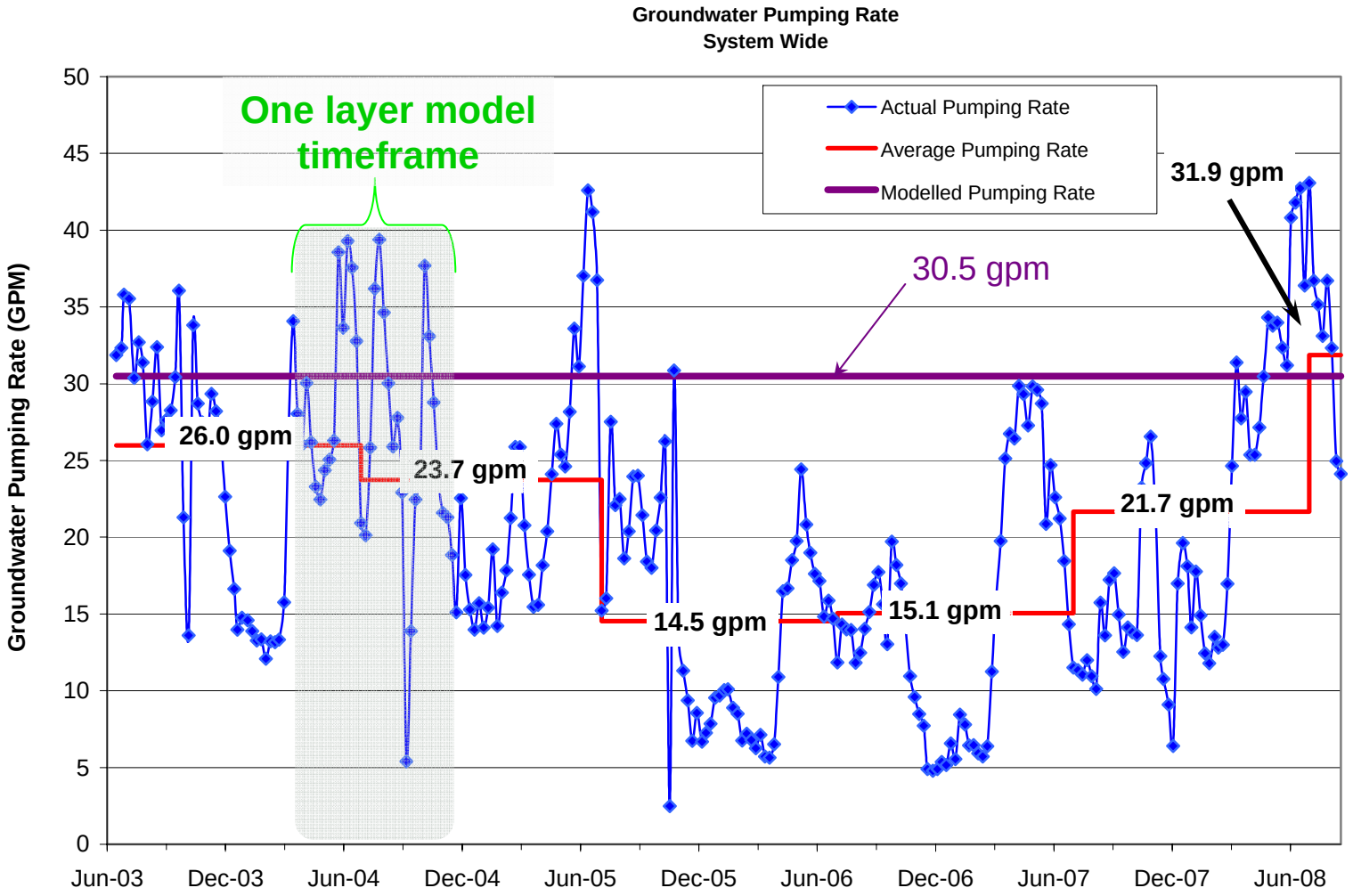
- **Was it that - the model or algorithms are pretty good but not that accurate?**
- **Was it that – the soil is too variable away from well?**
- **Was it that – the LNAPL Impacts vary away from well?**

Nope

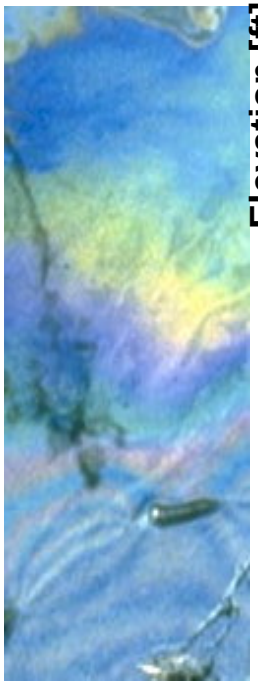


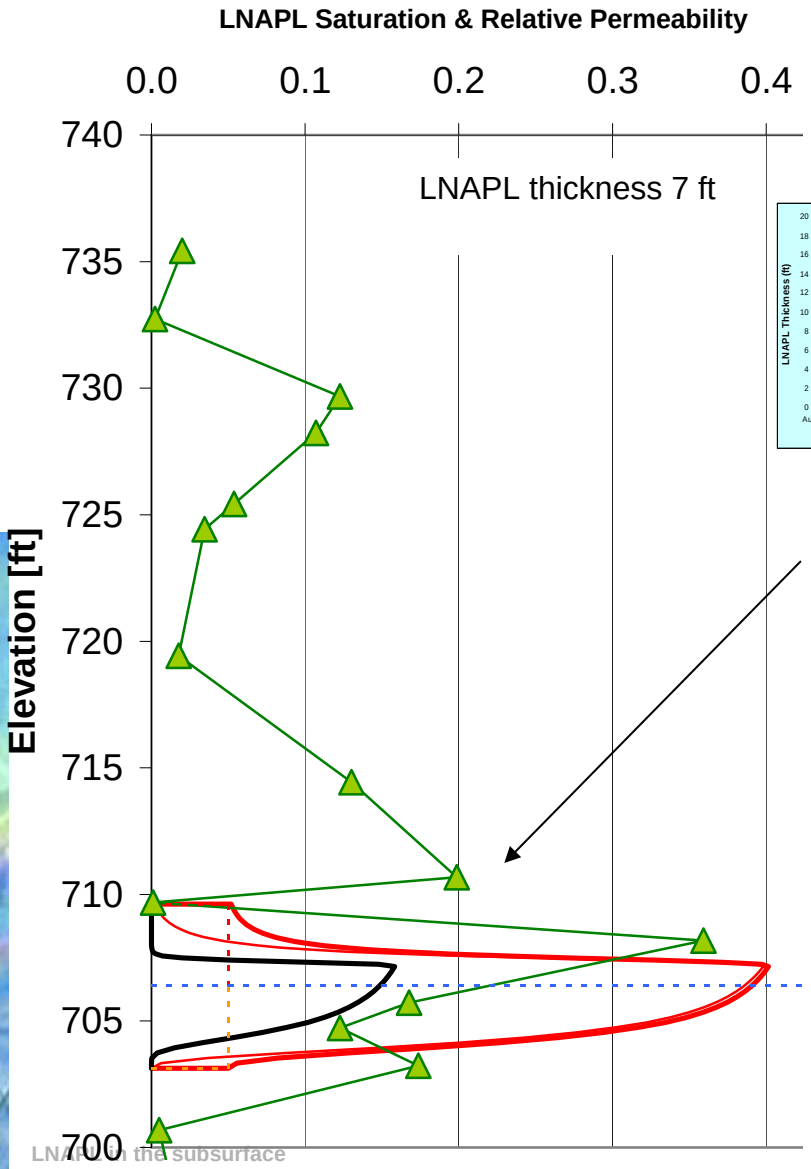
Water level in Missouri River makes constant pumping assumption difficult

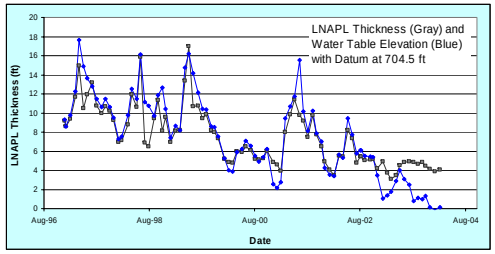




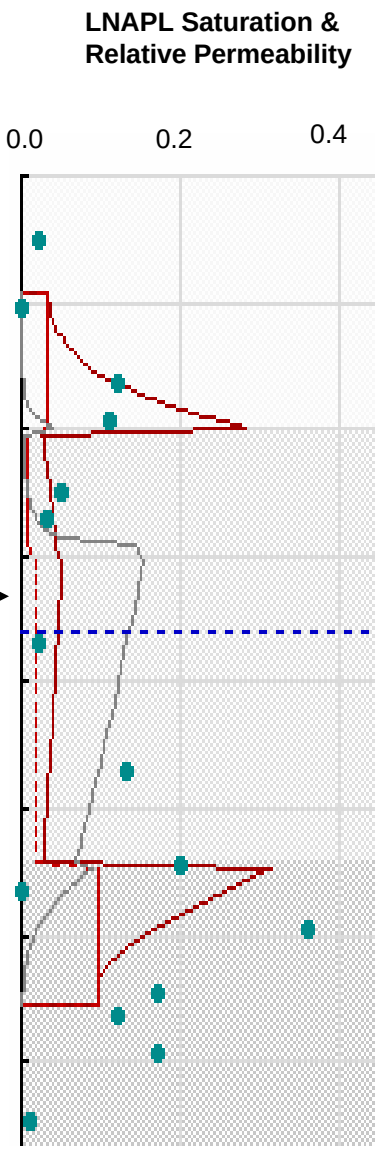
Vertical Distribution Comparison – 1 Layer versus 3 Layer







- LNAPL thickness 7 ft
- LNAPL thickness 18 ft
- 3 layer accounts SCM better
  - Layering
  - LNAPL thickness
  - etc



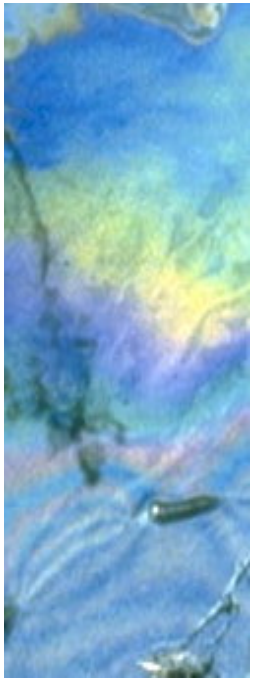
Models are non-unique solutions
The better model will correlate to more observations

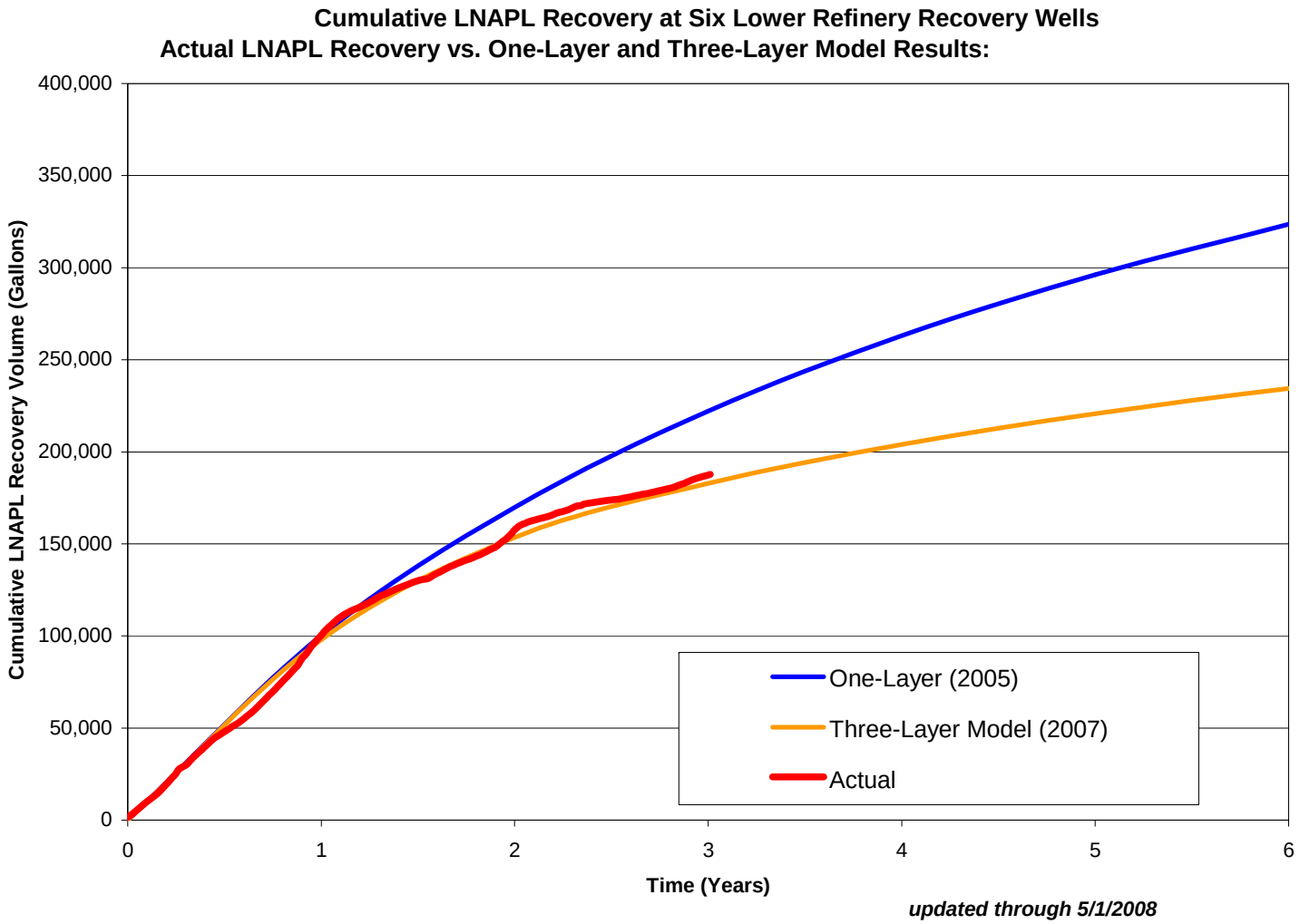
- January / February 2007 LNAPL recovery model at the site was revisited and updated using the latest understanding and newest three layer version of the API LDRM.
- Site conditions were unconfined and confined aquifer / LNAPL conditions versus the 1-Layer model assumed unconfined conditions
  - 1 Layer only modeled the sand layer that contained majority of LNAPL.
  - 1 Layer model could not account for large LNAPL thickness observed with
    ns.
  - cts of LNAPL recovery from the upper fine grained
    soil layer were not accounted for (but not a big deal)
  - 1 Layer model did not illustrate why higher water-table
    recovery rates or larger gauged thicknesses
    - At this site as water-table rose LNAPL thickness
    - 3 Layer model sets realistic expectation regarding large gauged thicknesses versus impacts by accurately accounting for the vertical variability of soil characteristics
- During the 3-layer model prep - accounting for variable historic water pumping rates was also identified as necessary for improved accuracy

Most Significant Difference for Vertical LNAPL Distribution

Most Significant Difference for Recovery Performance

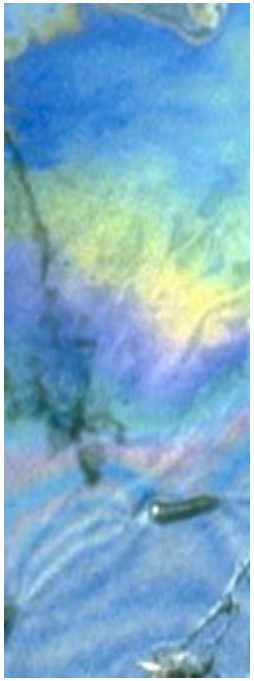
Updated site model with new 3 layer model
(initial 3 layer model from 2/07)

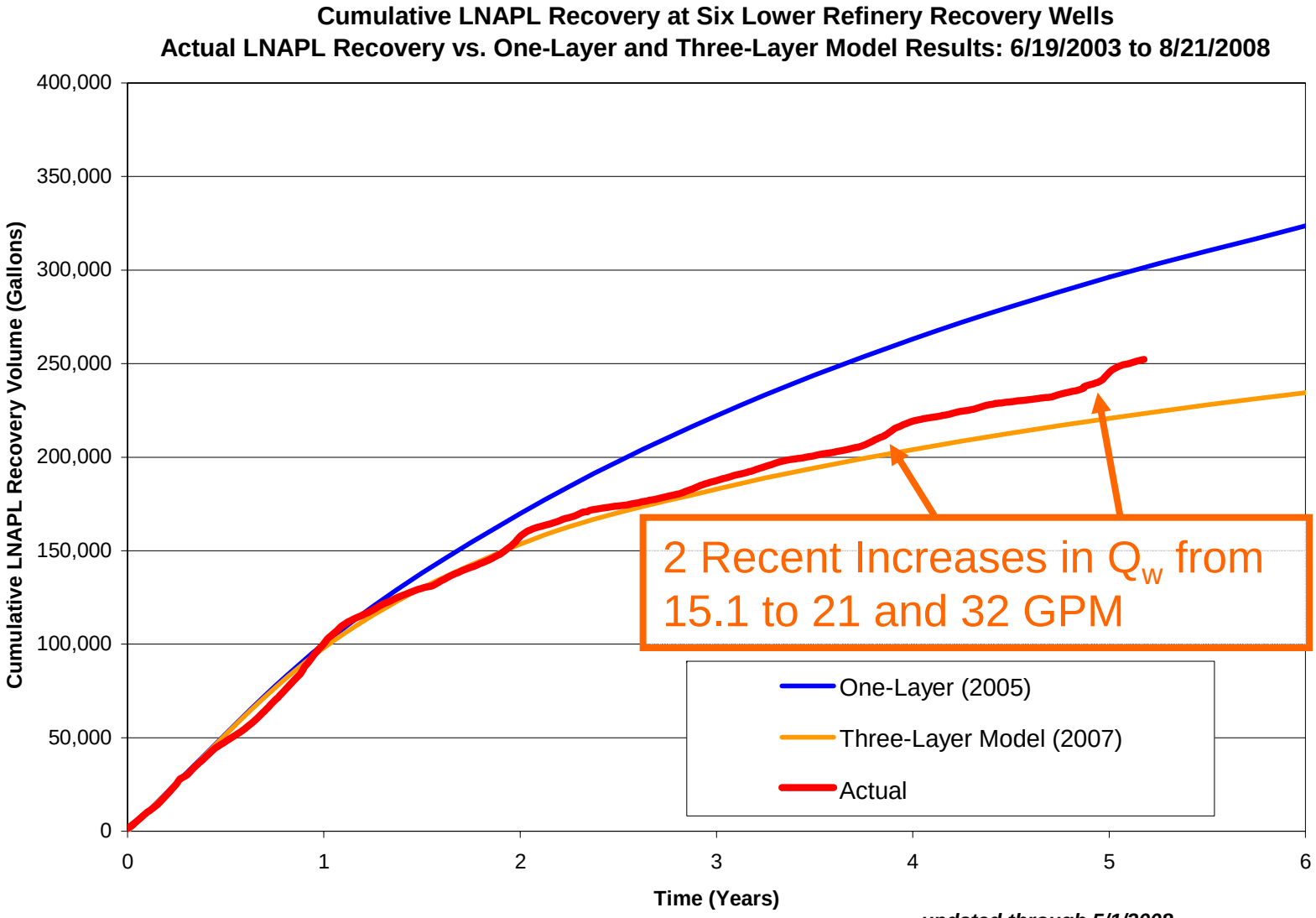




AK2

Updated site model with new 3 layer model (1.75 yrs of additional recovery)





updated through 5/1/2008

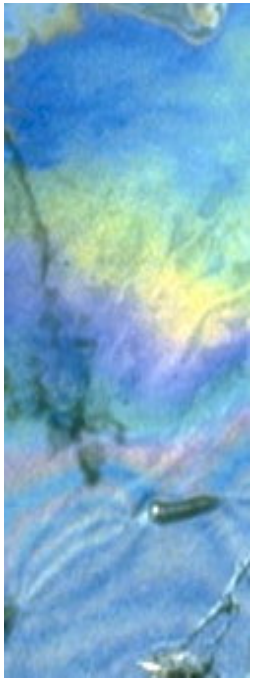
Slide 29

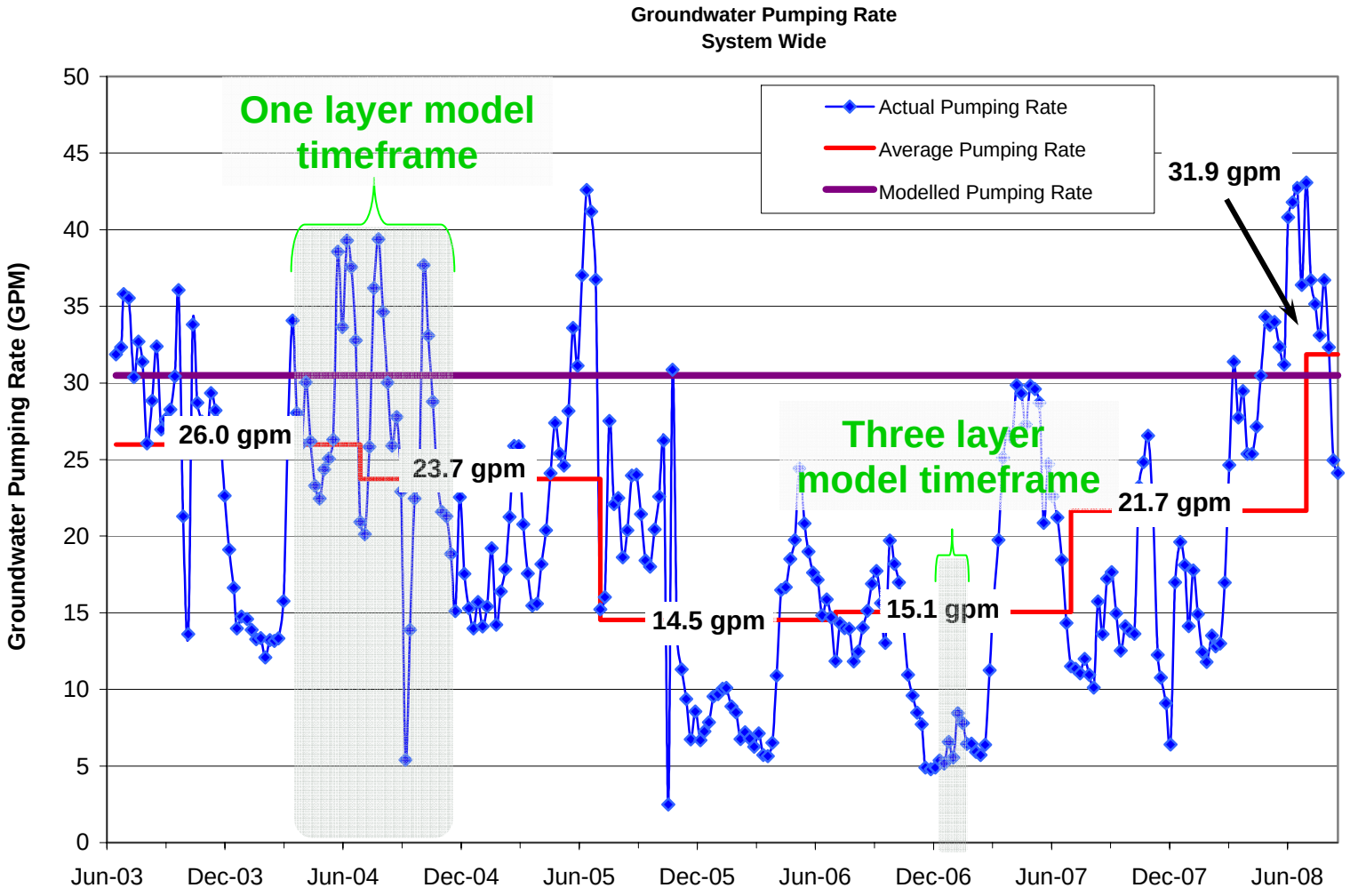
AK2

Mark, for this slide if you double click on the graph, the actual data spread sheet and the 1-layer model spread sheet are in here so you can update this graph as you like. You can make whaterver version you like, exit out of the excel sheet, make a copy, paste special as a metafile and then make a new slide with the picture but the data is then only in one slide to limit file size

akirkman, 8/28/2008

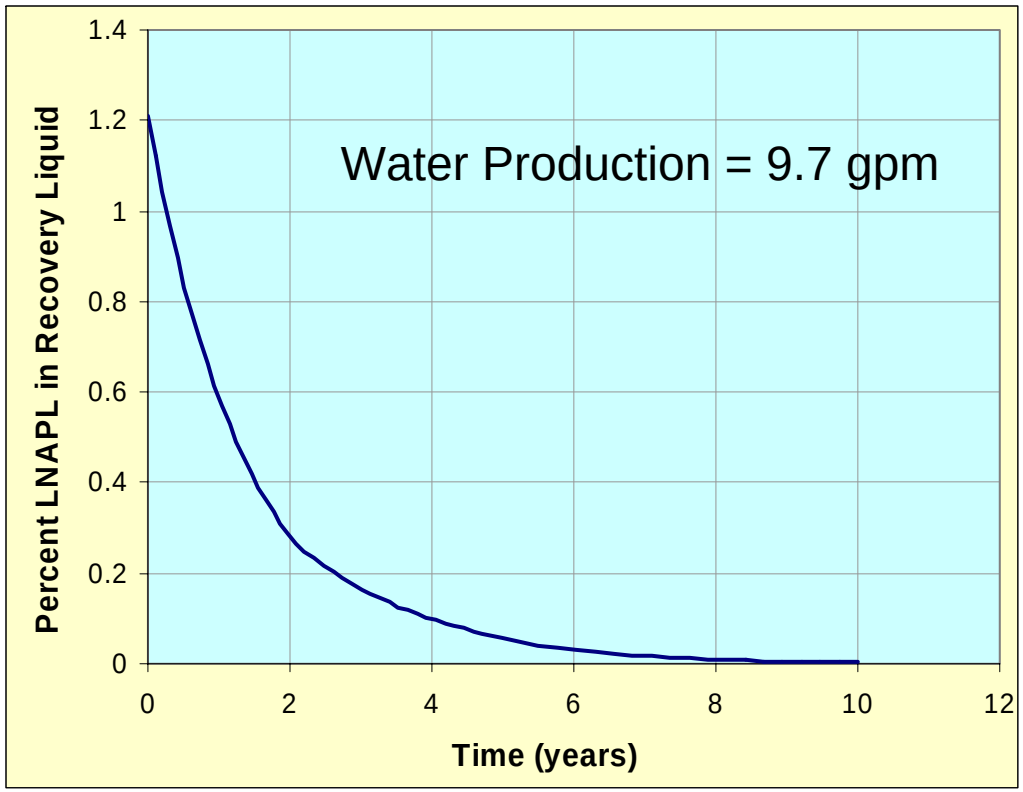
US Army Corp of Engineers makes constant pumping assumption difficult

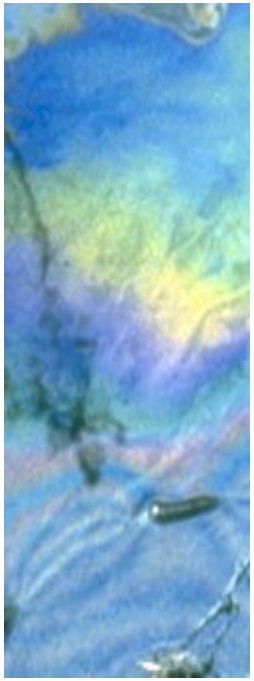




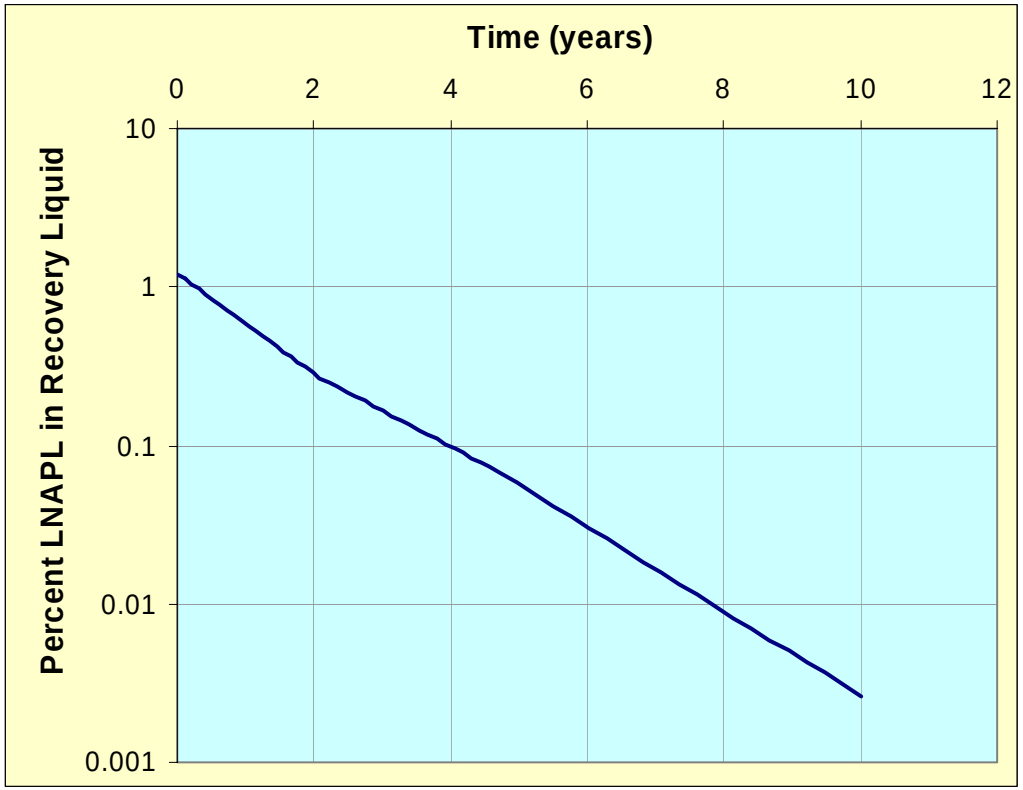
Recovery Endpoint – When to Stop LNAPL Liquid Recovery

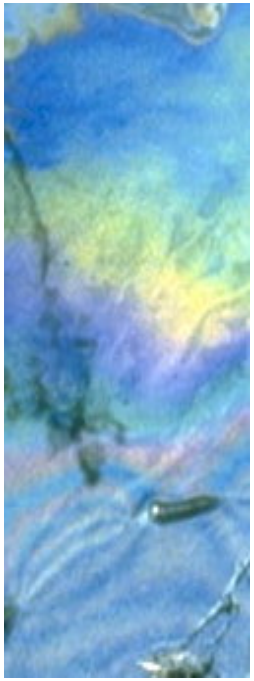
Performance-based endpoint: percent of LNAPL in recovery liquid → $Q_n/(Q_n + Q_w)$



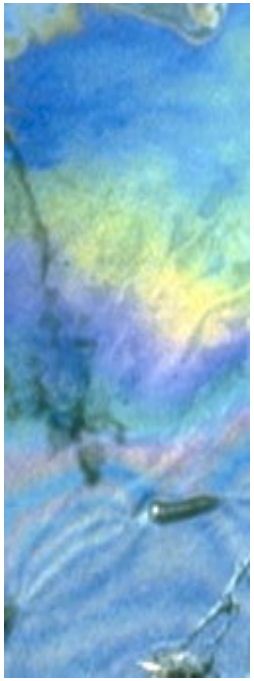


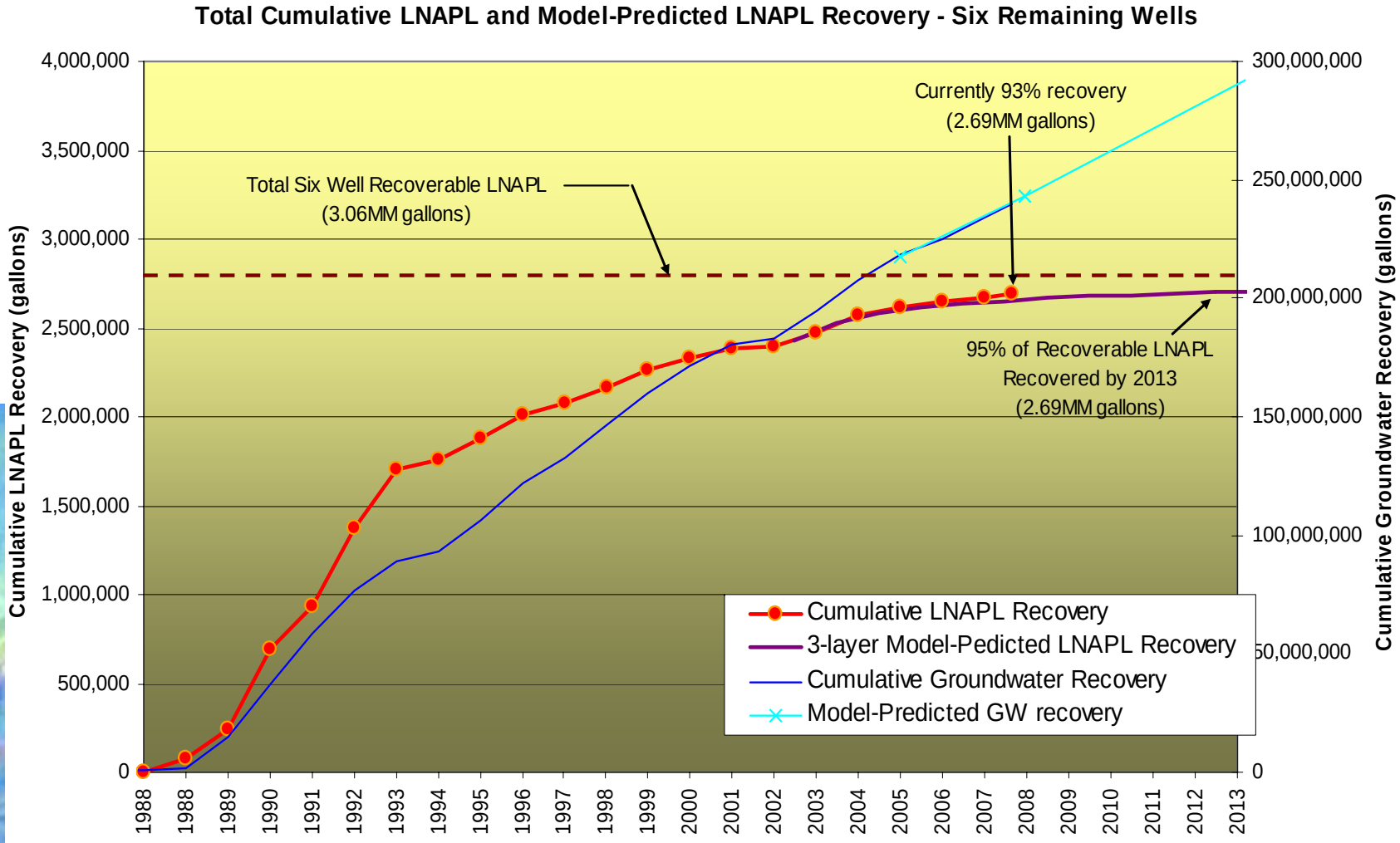
Same Data – Easier to pick endpoint





Cumulative well recovery: All wells since 1988 (approaching a natural endpoint for this system?)





Key Points

- API LDRM is a free and fairly simple tool
- With good site data and an accurate conceptual site model we can estimate LNAPL distribution in the subsurface
- With good site data and an accurate conceptual site model AND GOOD JUDGEMENT we can make good predictions for LNAPL recovery
- Combine all the above and with good understanding of LNAPL behavior, we can have more productive discussions about expectations for LNAPL recovery and ultimately LNAPL endpoints
- Progress of LNAPL recovery Estimates:
  - ✓ with the old pancake model – within two orders of magnitude
  - ✓ using the LDRM and site data – within one order of magnitude
  - ✓ careful use of the LDRM by an experienced user applying GOOD JUDGEMENT – within a factor of 2 to 3.